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Articles by OUGS Members,
the Annual Report for 2021
and the 2021 Moyra Eldridge Photographic Competition Winning and Highly Commended photographs

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DISSEMINATION OF INFORMATION PATHWAYS

Editorial:

Dear readers,

For a second year running we had to cancel our OUGS Annual Symposium owing to COVID-19 pandemic restrictions. But fortunately, barring unforeseen circumstances, we will *be able to hold our 50th OUGS Symposium this year. And even more fortunate for your Editor, it is to be held at the University of Surrey, which is 'just down the road', and will thus enable him to keep up with the local baseball here in our BBF Southern League.*

We have all participated in meetings on Zoom throughout the year, and learned a lot about coping and holding such meetings successfully. As one result, the OUGS accounts are in good shape too, as expenses have been at a minimum.

As I was last year, I am most grateful to OUGS Members who have submitted articles for the Proceedings*, as well as to many who wrote articles for their branch newsletters, several of which I felt should be shared with the entire OUGS membership. I chose these on the basis of their wide-ranging geological content, 'hot' topic value and quality, and often for their more unusual subject matter. The Earth Sciences embrace a wealth of inter-disciplinarian content and it is always heartening to learn the varied interests of our members.*

So, in this issue we travel from the celebration of 'women in rock' to someone's favourite fossil. Between these articles we learn about Cambridgeshire chalk, 'brockram' in Cumbria, tectonic geology in Assynt and NW Scotland, the post-glacial landscape of Bas Chablis, Haute Savoie in south-eastern France, petrified trees in Calistoga, California, volcanoes on the Banks Peninsula in New Zealand, fossil hunting in Morocco, ancient-to-recent copper mining in Cyprus, life in exploration geology in Western Australia and the Canadian Yukon, reminiscences of Iceland's Eyjafjallajökull 2010 eruption, Torquay 'marbles', Neolithic and Bronze Age Britons' use of geological resources and how to make a bronze arrowhead, fossil corals, Antarctic Bottom Water, polygonal columnar jointing in the southern English Lake District, and a theory about why their was a Cambrian Explosion 2.5 billion years ago.

I would also like to express, on behalf of the OUGS, our gratitude to publishers for their continued generosity in supplying us with numerous new books to review, a total of 22 this year, ranging through a myriad of Earth Science themes, research, guides and manuals. And of course I personally thank all our member reviewers for writing these reviews. And this year we have a 'first' — our first Podcast review by member Caroline Peters, of Geology Bites*, the creation of member Oliver Strimpel.*

I hope there is something for everyone here and, as always, wish you

Happy reading and good health,

— David M. Jones, OUGS Proceedings Editor

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The Editor would like to give his sincere thank-you to fellow OUGS Members who gave him invaluable help with all aspects of this issue of the *OUGS Proceedings*: to the authors for their cooperation and timely responses to my many editorial queries; to President Angela Coe, OUGS Chair Jannet Hiscott, OUGS Secretary Pauline Kirtley, OUGS Membership Secretry Sally Munnings, and OUGS Treasurer and Webmaster Stuart Swales for their advice and encouragement; to OUGS Members Rosemary Darby and Anne Jones for their diligent proofreading; and to Anne Jones for her suggestions and advice regarding the cover layout and design.

Erratum: In *OUGS Proceedings* 7, 2021, I most sincerely apologise to Karen Wade for leaving her name off (!) her splendid photograph 'The prehistoric forest on the beach at Borth, west Wales', Popular Vote Winner in the Moyra Eldridge Photographic Competition for 2020.

Pioneering women in rock: some notable female geologists

Paul F. V. Williams

Introduction

On March 8th 2021 we celebrated International Women's Day, where we recognised and championed the achievements of women across the world. This year's IWD theme 'Choose To Challenge' was a celebration of women who have challenged the so-called 'established order' of our patriarchal society and have taken up traditionally male roles in the quest for proper and rightful equality.

To support these aims and ideals I championed the achievements of some notable pioneering woman geologists and wrote a piece for our NOUGS Facebook Group page, which some of you may have read. That piece was an extract from a slightly more detailed version, which is now presented below. For an excellent discourse on pioneering female geologists I can recommend Cynthia and Bettie's Geological Society of London (GSL) Special Publication volume (Burek and Higgs 2007). *[See also, review of Burek and Higgs 2021* Celebrating 100 Years of Female Fellowship of the Geological Society: Discovering Forgotten Histories *by Helen Coombs, this volume. — Editor]*

It is important to place into context the situation women found themselves in the late 1700s, when our story begins. If you were born of the wealthy classes, women would have had an education that would have set them up for their charted aim in life — finding a husband. Once that was achieved, as a woman that would have given you some sort of social and financial security. Being born into the working classes was, however, a totally different situation, where girls would have had very little, if any education. That makes the story of our first woman pioneer geologist all the more remarkable.

A pioneer palaeontologist

Mary Anning was born into a poor family in 1799 in Lyme Regis (Fig. 1). And it was fortuitous that she had been born in exactly the right spot! Anning's father made a living as a cabinetmaker and shopkeeper, and also sold, of all things, local fossils to the early Georgian tourists who frequented the area and were keen to pick up local curios and novelties. Mary entered into the world of fossil collecting at an early age by the side of her father, learning to recognise things that would sell well in the family shop. Here Mary was practising that fundamental learning strategy, that of 'learning by engagement'.

She became adept at recognising fossils and was soon out collecting on her own, or along with her elder brother. At age 12 Mary diligently unearthed a 15 m long skeleton of a marine creature, after her brother had found the exposed skull. This turned out to be the very first discovery of what was later called an Ichthyosaur. And it was during the study of this specimen that another of Mary's skills came to light, as a talented illustrator. Keen to share her discovery with learned palaeontologists, she meticulously drew the specimen from many angles and in great detail, relying on the very few academic skills she possessed: those of reading and writing. But she also proved herself to be an excellent scientific communicator as well, relaying all her observations to the greater scientific community.

Intrigued by these discoveries she wanted to know more and began to teach herself anatomy and palaeontology. In her early twenties Mary discovered another 'first' in reptile palaeontology: the first complete skeleton of a Plesiosaur.

Figure 1 A portrait of Mary Anning with her dog Tray and the Golden Cap outcrop in the background. From a drawing by B. J. M. Donne in 1850 (Public Domain).

In 1828 she unearthed yet another 'first', this time the well-preserved remains of the winged dinosaur, later named Dimorphodon, a Pterosaur. This was the first one ever discovered outside Germany.

Despite her lowly upbringing she communicated extensively with the notables in the geological community of the time and became well respected and well known by the scientific community. Many of her scientific contemporaries wrote about, documented and discussed her amazing findings, but without proper acknowledgement to her as the source; and much of her writing was plagiarised. Hence she remained largely unknown to a wider audience. Because she was a woman, she was not allowed to present papers on her work to the GSL, which did not admit women. The Society did, however, support her financially in recognition of her work.

She was well known and visited by the great and good of geology, and became close friends with the Murchisons, conversed with Sedgwick, and was well respected by all, especially by her wealthy patrons. She communicated with Charles Lyell and conducted fossil-hunting trips for and with the palaeontologist Louis Agassiz, the latter holding her in high esteem.

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Life was still difficult for her with poverty never far away, and childhood friend Henry De la Beche sold prints of his painting of an early Jurassic land/seascape for Mary's financial support. William Buckland persuaded the British Academy and the British government to award her an annuity in recognition of her immense contributions to knowledge, and as ill-health overtook her the GSL raised financial support for her.

She has been recognised subsequently with her name appended to numerous reptilian fossil species and even genera in her honour. The Natural History Museum, London has a series of rooms that bear her name, in recognition of her remarkable contributions. A statue of her is also being planned, to be erected in her home town of Lyme Regis. Truly an amazing woman pioneer in the science of geology.

[For further details of Mary Anning's life see also Averil Leaver's article in this volume — Editor.]

Admission of Female Fellows to the Geological Society of London

The fact that Mary Anning could not be admitted to the GSL because women members were not allowed prompted me to search for when they first admitted women as Fellows of the Society: not until 1919!

The first female Fellow of the Geological Society of London was Margaet Crosfield (1859–1952) (Fig. 2), admitted on May 21st 1919, one of a number admitted on that date, others of whom are also mentioned below the photograph. Crosfield worked on the Silurian of the Welsh Borderlands; her major geological papers, co-written with Ethel Skeat and Mary Johnston (who were also among the first elected batch of female Fellows) were on the Palaeozoic strata of Wales and Shropshire. Crosfield's and Skeat's paper. 'On the geology of the neighbourhood of Carmarthen' (Crosfield and Skeat 1896) and was so highly regarded that it formed the basis of the geological map produced by the British Geological Survey for the area.

Figure 2 Margaret Crosfield at Leith Hill, at a GA Field Meeting (front left) (image "Digitised from the Geologists' Association Carreck Archive, reproduced with permission of the British Geological Survey").

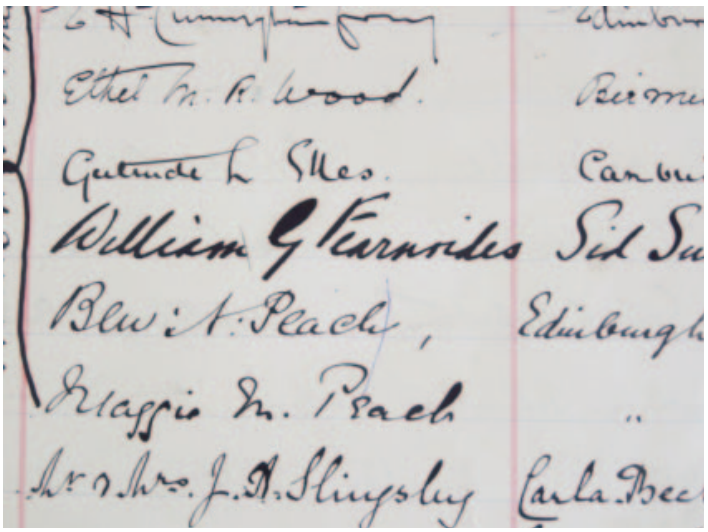

Figure 3 Entries by Gertrude Elles and Ethel Wood in the Inchnadamph Hotel Visitors Book, 1912.

Two more geological pioneers

The next two pioneering women geologists came to my attention while examining the guestbook for the Inchnadamph Hotel in Scotland's NW Highlands (Fig. 3). It was at this hotel that Ben Peach and John Horne stayed while conducting their monumental work unravelling the geology of the Assynt area. In September 1912 The British Academy invited Peach and Horne to lead a field visit for many of geology's notables at the time, so that Peach and Horne could demonstrate their findings first hand, as published in the classic memoir of 1907 (Peach *et al.* 1907). The field meeting was based at the Inchnadamph Hotel.

The names of Gertrude Elles and Ethel Wood appear in the guestbook several times, alongside that of Charles Lapworth. Having their names in the guestbook had to mean that these were significant women, since the only other female names were those of the spouses of the eminent professorial visitors. They turned out to be more pioneering woman geologists.

Gertrude Elles MBE (1872–1960) was another legend of rock (Fig. 4, *opposite*). She was a graduate of Newnham College Cambridge with first-class honours in the natural sciences Tripos. After Cambridge she went on to conduct research on graptolites for her doctorate, graduating with a DSc from Trinity College Dublin in 1905. During this time she was awarded the GSL's Lyell Fund to support her research, but since she was a woman she was not allowed to collect the award in person. After Dublin she became the first female lecturer at Newnham College Cambridge, the first woman to receive a Readership, and became vice-principle of Newnham College in 1925 as the first ever woman to take up this position. She was in the first cohort of women elected as Fellows of the Geological Society of London in 1919, and became the first female Council member of GSL in 1923.

Working on graptolites along with Charles Lapworth and fellow Newnham alumnus and friend Ethel Wood *(see below),* she produced the first detailed and much-acclaimed monograph on British Graptolites (Elles and Wood 1918). Elles worked on the text of the monograph, while Ethel Wood concentrated on the illustrations. This became a benchmark work, and is still in use today. In recognition of the importance of this work she was awarded the GSL's Murchison

Figure 4 Gertrude Elles (fBurek 2014; accessed from U Chester Digital Repository cc/by-nc-nd/4.0).

Medal in 1919, the first ever female recipient. Ethel Wood received the Murchison Medal for this work the next year.

After preparing and writing the memoir Elles worked on the evolution of graptolites, concentrating on fossil communities rather than on individuals, thus bringing a new dimension to palaeontological study. She then turned her attention to biozone stratigraphy, which enabled global Lower Palaeozoic stratigraphic correlation to be realised. When we think of graptolite stratigraphy and zonation of the Palaeozoic the name of Charles Lapworth comes to mind. But it is important to recognise that Elles and Wood were just as significant, if not more so.

The other contributor to the research on graptolites, and the second signatory in the Inchnadamph guestbook, is Ethel M. R. Wood. Her name occurs consecutively with that of Gertrude Elles.

Ethel Wood (1871–1946) (Fig. 5), was another graduate of Newnham College Cambridge with first-class honours in natural sciences. She then became a research assistant working with Charles Lapworth, and gained her D.Sc. from the University of Birmingham in 1906. Wood was a college friend of Elles, and continued her own work on graptolites as her contribution to the compilation of the epic monograph. In recognition of this work she was awarded the GSL's Murchison Medal in 1920, having been another of the first female Fellows of the Society admitted in 1919. After marriage she became a significant public figure and dedicated the rest of her life to public service, for which she was awarded DBE, becoming Dame Ethel Shakespear. She was a Justice of the Peace, and was a notable philanthropist, and spent much time working with the poor and with disadvantaged families.

Into the 20th century

My next pioneering female geologist is Marie Tharp. Her research brings us into the 20th century and the early days of the evolving theory of plate tectonics, itself a major revolution in Earth science. This revolution was fuelled by numerous independent pieces of evidence that eventually became linked to form the theory of plate tectonics. Without the work of Marie Tharp, who identified a cornerstone piece of evidence, plate tectonics would have taken much longer to become recognised and established into mainstream geological understanding.

Marie Tharp was a trained geologist and cartographer. Working at Lamont Geological Observatory on the physiography of the North Atlantic Ocean sea floor with Bruce Heezen in the early 1950s she pieced together data from bathymetric profiles obtained from ship-borne surveys and discovered a ridge-like feature extending N–S through the whole of the ocean basin. Crucially, she identified in this feature what she thought was an axial rift-valley throughout the whole of the ridge's length. She ascribed this rift to a site where the ocean floor was being pulled apart. At the time, this evidence would have supported the hypothetical and controversial notion of continental drift. However, apparently Heezen discounted her suggestions, reputedly as 'girl-talk'! Only when it was subsequently found that earthquake epicentres coincided *exactly* with Tharp's proposed rift valley, thereby confirming her original suggestion, did Heezen accept this idea. The first sea-floor map of the North Atlantic was published in 1959 by Heezen, Tharp and Ewing, and cited as major evidence to support the idea of continental drift and plate tectonics. Tharp, however, was not recognised in publications by Heezen on continental drift during that time.

Tharp continued working on ocean basins worldwide, and discovered that the axial rift she had identified in the Mid-Atlantic Ridge was in fact a global feature. Wherever there was a mid-ocean ridge, it had an axial rift. Armed with this additional data she, along with Bruce Heezen, compiled the now legendary map of the world ocean floor, published in *National Geographic* in 1977 (Fig. 6, *overleaf*). This was a fundamental contribution both as the first ever detailed map of ocean floor physiography, and as one of the most significant contributions as evidence for the operation of sea-floor spreading, continental drift and plate tectonic processes. And this was down in great part to the work of one remarkable woman. We talk of William Smith's map as 'The Map that changed the World'; Marie Tharp's map was the one

Figure 5 Ethel Wood (Burek 2014; accessed from U Chester Digital Repository cc/by-nc-nd/4.0).

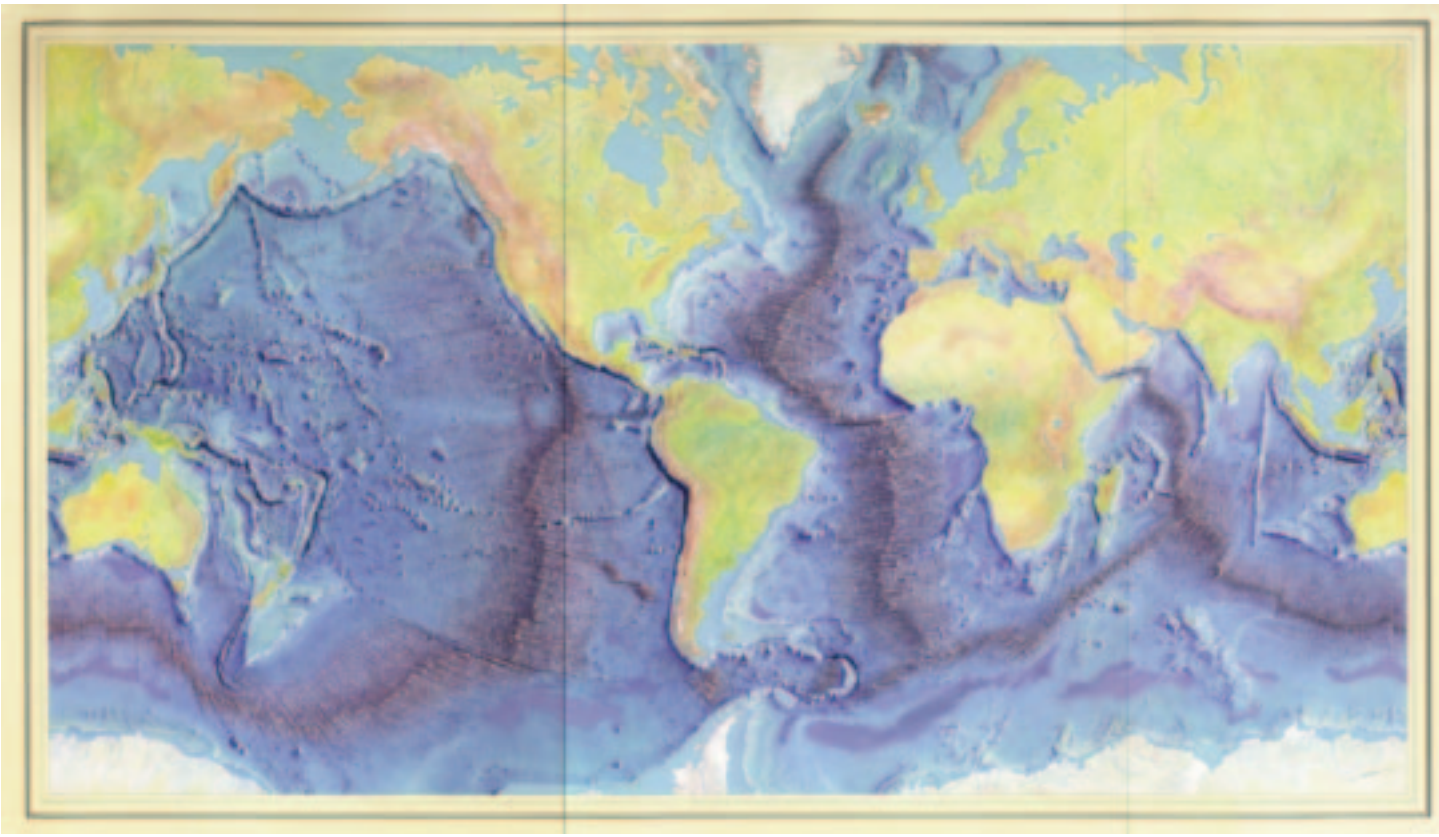

Figure 6 World Ocean Floor Panorama: the map that changed our understanding of how the Earth works Heinrich Berann's painting of the Mid Ocean Ridges 1977, by Tharp and Heezen (Public Domain).

that changed the *Planet*, and our understanding of how it works. *[For further details of Marie Tharp's life see also Colin Morley's article in this volume — Editor.]*

Beyond the Earth

My final female pioneer and woman champion has an 'other worldly' claim to geological fame. Linda Morabito made her discoveries when society and academia had realised the true value of women's contributions. She was a NASA scientist and engineer working on the Voyager missions to deep space. During her studies of images from the Jovian satellite Io in1979, she discovered the very first evidence of volcanic activity on a Solar System body other than the Earth (Fig. 7).

Today we recognise the Solar System as an active place, with numerous manifestations of volcanism in many diverse planetary settings. But back in the 1970s this was all unknown. We believed then that only our own planet was volcanically active. Thanks to this monumental discovery made by Morabito we now know something of what goes on inside some of those distant planetary worlds; a true revelation! She has received due recognition for this epic discovery during her lifetime. A success story for women's emancipation. *[See also, review of Natalie Starkey 2021* Fire and Ice: the Volcanoes of the Solar System *by David M. Jones, this volume — Editor.]*

Figure 7 Volcanism on Io, discovered by Linda Morabito (JPL/NASA Image, Public Domain).

Conclusion

All these women were truly amazing pioneers. The six eminent women of geology discussed above need to be remembered for their massive contributions both to the science of geology and to the cause of women's equality. And all rightfully deserve to be known and recognised as immensely significance ambassadors for women in rock.

References

Burek, C. V. 2014 'The contribution of women to Welsh geological research and education up to 1920'. *Proc Geol Assoc* **125**, 480–92

Burek, C. V., and Higgs, B. (eds) 2007 *The Role of Women in the History of Geology.* London: Geol Soc Spec Publ 281

Crosfield, M. C., and Skeat, E. G.1896 'On the geology of the neighbourhood of Carmarthen'. *Quart J Geol Soc* **52**, 523–41

Elles, G. L., and Wood, E. M. R. 1901–1918 *Monograph of British Graptolites. Parts 1–11*. London: Palaeontological Society Monographs, 1–539

Peach, B. N., Horne, J., Gunn, W., Clough, C. T., Hinxman, L. W., and Teall, J. J. H. 1907 T*he Geological Structure of the North-west Highlands of Scotland*. Mem Geol Survey GB

(An earlier version of this article was originally published in the Northumbria Branch Newsletter March 2021 — Editor.)

Mary Anning (1799–1847), Fossil hunter extraordinaire

Averil Leaver

On my retirement from the post of Treasurer for Severnside Branch, I was presented with a gift voucher which I have spent on some commemorative coins as a remembrance of OUGS and its importance to me. I would like to share with you the story behind these coins.

In spring 2021 the Royal Mint issued a set of 50p coins (Fig. 1) to commemorate Mary Anning and her largely unrecognised work in the early years of fossil collecting and interpretation. In the early days of the science of Palaeontology there was a group of Natural Philosophers and Geologists collecting and classifying fossils, but they were mostly men. Women were not regarded or recorded as participating in this occupation. This issue of coins is to help rectify this omission.

Figure 1 Set of 50p coins issued by the Royal Mint in spring 2021 (https://www.royalmint.com/our-coins/events/the-mary-anning-collection/2021mabu-a734d6f1/ (Royal Mint M. Anning set).

A brief history of her life

In 1799 Mary Anning was born into a poor family, one of 10 children of whom only two reached adulthood. The family were living in Lyme Regis in Dorset, where the coast was made up of cliffs of Jurassic blue Lias through to Middle Cretaceous Green Sand, rich in fossils. Her father, Richard Anning (*c.*1766–1810), was a cabinet maker who tried to increase his income by collecting these fossils from along the cliffs to sell to the tourists who came to the picturesque coastal village. Unfortunately this dangerous occupation may have brought about his early death, age 44, due to a fall from the cliff, compounded by his having tuberculosis.

Although little is recorded about her early life, Mary was literate, could draw well and appears to have had an open and enquiring mind. Her education was limited to the local Sunday School, but she made good of opportunities to borrow and copy volumes and papers that furthered her knowledge. Mary taught herself anatomy and the structure of the skeleton so as to be able to identify the bones she found. She also taught herself French so that she could read the works of Georges Cuvier (1769–1842), a French Naturalist and Palaeontologist. As she grew older she was able to converse as an equal with the scientists that were drawn to Dorset by the emerging fossils and became familiar with William Buckland, Richard Owen, Adam Sedgwick and Roderick Murchison, among others.

Mary was 10 years old when her father died, with one surviving brother, Joseph, who was three years her senior. Both lived with their mother. The family was in debt to £110 and struggling financially. At this time this amount of money would have been the equivalent of two years' wages for a skilled tradesman. Both of the children had helped their father collect and prepare fossils and they continued to try to earn money through this means, although Joseph was also an apprenticed upholsterer. Despite finding the first Ichthyosaurus to be fully described, and selling it for £23 in 1815 (Fig. 2) the family needed the support of the parish for five years. On completion of his apprenticeship Joseph left home and worked full time as an upholsterer, making a success of his trade. Thereafter Mary tried to support herself and her mother by her fossil collecting ,with varying degrees of success. Some of her more famous finds were turned down by major museums as they were reluctant to pay a competitive price for these rare fossils.

As a fossil finder Mary would spend some of her time walking the beach below the cliffs, using her sharp and increasingly discerning eyes to search the cliffs for fossils that would appear in the eroded strata or in large blocks dislodged from the cliff face. Winter months were prime times for this occupation, as the stormy weather increased the erosive power of the sea. The bulk of her finds would be ammonites, nautiloids, belemnites, crinoids and other small creatures preserved in the soft shales. Once collected she would carry them home to prepare and record them (drawing was a skill she developed). These formed the basis of her trade with the increasing tourist visitors. If on her walk she spotted a larger animal emerging from the soft rock she would leave a marker — her faithful dog, Tray — and hurry home for tools and to seek assistance from the local fishermen. But the find of a large fossil was a rarer occurrence and the start of a careful process to prepare, draw and try to describe in order to have a good product to offer her prospective customers in the scientific community.

From 1810 to 1820 Mary's mother (also Mary, but sometimes known as Molly, née Moore, 1764–1842) was running the business, but as young Mary grew in experience she took over. The first evidence of this was a receipt for a fossil that she had sold to Adam Sedgwick (1785–1873) in autumn 1820.

Figure 2 Ichthyosaur head in the Sedgwick Museum, Cambridge, thought to have been found by Mary Anning and purchased by Adam Sedgewick (https://scienceoveracuppa.com/2017/04/23/in-mary-annings-footsteps/ Emily Casanova Ph D 13/07/2021 10.26).

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Figure 3 Illustration of Ichthyosaur head from memoir by Sir Everard Home F.R.S. (composite) (Home 1814; accessed from JSTOR 80.6.156.20 on 25/05/2021 15.00).

At this time there was a wealthy family of three sisters settled in Lyme — Margaret (?–1845), Mary (1773?–1838) and Elizabeth (1780–1857) Philpott. They were collecting an important set of fossils, which were later donated to Oxford University Museum. Many of these fossils may in fact have been found by Mary Anning, but their source was never recorded. Another collector, a retired Life Guard who settled in nearby Charmouth from 1818, did recognise the finder of his specimens. Lt Col. Thomas James Birch (1768–1829) became the family benefactor in 1820 when he auctioned his collection and gave the £400 proceeds to the Annings to help overcome financial difficulties arising from a poor year of searching for good specimens. He had realised in his dealings with the family that most of the good specimens from the locality and described in scientific literature had originated through this family's endeavours.

Another of the regular visitors to this coast was William Buckland (1784–1856) and his wife Mary (née Morland, 1797–1857). Mary Anning and William Buckland would go on fossil-hunting expeditions together; and one common interest of theirs was searching for and studying coprolites. Mary had long noticed that coprolites were associated with the digestive systems of the fossils that she found and in some cases the bones of the last digested meal were still evident and recognisable in the coprolites. Buckland published studies of coprolites and later acknowledged Mary's early recognition of their true nature and origin. Buckland also supported Mary by promoting her finds to his friends and colleagues. In one instance he bought a Plesiosaur specimen that the British Museum had declined and then donated it to them.

Mary Anning was also friends with the Murchisons, Roderick (1792–1871) and Charlotte (1789–1869, née Hugonin). Charlotte was a particular friend to Mary and had her own collection of fossils, and was equally as well versed in geology as her husband. In July 1829, on the only occasion that Mary went to London, she stayed with the Murchisons and they showed her the sites, including the British Museum and the Geological Society, as she later recorded in her diary.

It appears that Mary had little in common with the local population as she had improved herself and was more of an equal with the people who came to buy her fossils. Her scientific knowledge enabled her to hold her own in discussions with the male scientists. The local townsfolk admired Mary and valued her as an asset to the town through her notoriety and as an attraction to a valuable tourist industry.

In 1838 Mary gained some recognition of her work and discoveries when the British Association for the Advancement of Science granted her an annuity. The £25 per year was derived from a private subscription by the members of £200. A further grant of £300 was given to Mary by the UK government through the auspices of Prime Minister William Lamb, Lord Melbourne.

Mary's mother died aged 78 in 1842, but Mary continued working. However, within three years she was suffering from breast cancer, from which she died on 9 March 1847. She was buried in St Michael's Church in Lyme Regis above the cliffs that she had searched throughout her life for the fossils that made her famous.

Fossils commemorated on the 2021 50p coins

The Ichthyosaurus species, *Temnodontosaurus platydon*

Mary Anning has been credited with finding several good, near-complete specimens of Ichthyosaurus, but she is seldom named in the records as the finder. Museum records usually name the donor who purchased the specimen from Mary, but not the person who found and prepared it.

The first Ichthyosaur that the Annings found was a joint effort. Joseph found the head in 1811 and Mary found the rest of the animal in the next season, she was only 12–13 years old at this time! The fossil was sold to a local fossil collector, Henry Hoste Henley Esq. (1766–1833) for £23. It was described in 1814 by Sir Everard Home (1756–1832) (Fig. 3) and changed hands to eventually be donated to what is now the Natural History Museum

Figure 4 Illustration of Temnodontosaurus platydon (Ichthyosaurus platydon) *as drawn by William Buckland (Buckland, William, Pickering, William, and Whittingham, Charles 1836; accessed via Google Books 21/05/2021).*

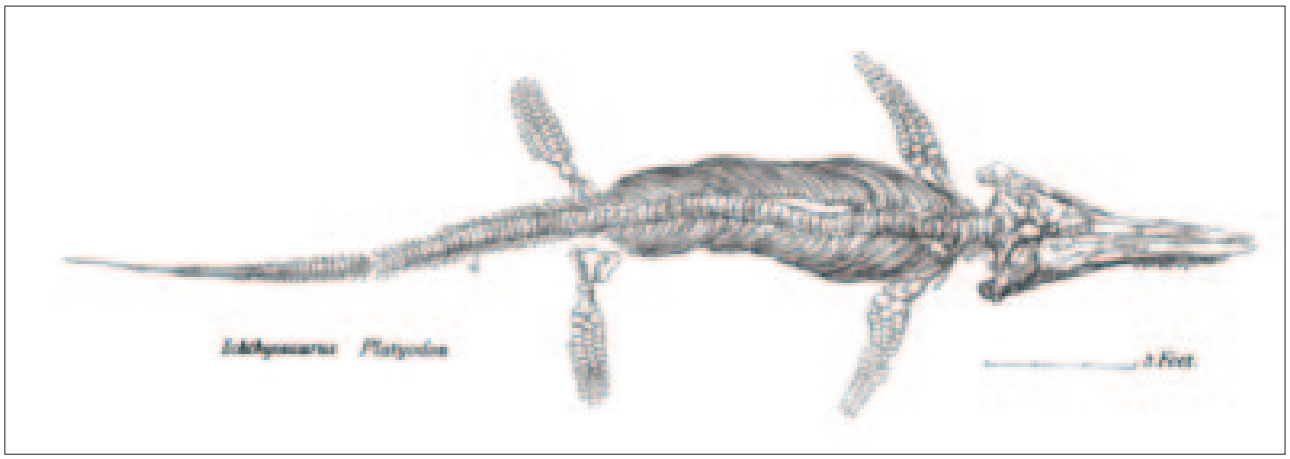


Figure 5 Illustration of Anning's Plesiosaurus prepared by Thomas Webster 1824 Trans Geol Soc ***1,*** *plate 48. (https://www.biodiversitylibrary.org/page/36238986#page/617/mode/1up digitized by California Academy of Sciences; accessed 16-07-2021).*

(NHM). Unfortunately, for some unknown reason they only have the head now! How do you loose a large fossil?

An Ichthyosaurus was a marine dinosaur more than 10 ft/3 m long, with a fish-like appearance and four paddle-shaped limbs. The head was a third of its length, with long tooth-filled jaws and huge eyes that may have enabled it to see its prey in murky water.

Mary went on to find many other Ichthyosaur specimens and bones, which she sold to museums and collectors, including several to Adam Sedgwick. Unfortunately, some of these specimens were lost or destroyed in WWII and many are not attributed to Mary Anning as initial collector. *Temnodontosaurus platydon* is the largest species that she found, and is the species named on the Royal Mint coin. *Temnodontosaurus platydon* was described and named by Rev. William Conybeare (1787–1857) (Fig. 4, *previous page*) and this specimen is now held by the Natural History Museum as the holotype for the species. Some specimens reached more than 20 ft/6 m in length.

Plesiosaurus, *Plesiosaurus dolichodeirus*

Mary found this fossil in December 1823, and it is recorded that she extracted it from the Black Venn cliffs within 24 hours of the find — was the weather bad at the time? This was some feat as the almost complete specimen is 9 ft/2.75 m long. The scientific community must have been excited by this strange animal, as within three months it had been bought by Richard Grenville, Duke of Buckingham (1776–1839), examined by William Conybeare, and described to a meeting of the Geological Society in London on 20 February 1824 (Fig. 5). This specimen became the holotype following William Conybeare's description and naming and is also now in the NHM, where it is correctly attributed to having been found by Mary Anning.

This strange marine 'lizard' had a shortish tail, broad, flat body with paddle-like flippers, a very long neck and small head. It was a strange animal that some described as combining the teeth of a crocodile, a snake-like neck and the flippers of a whale. It is no wonder that, when George Cuvier first read the description and studied the drawings, he doubted the truth of this strange creature and suspected that it had been constructed from different animals and was a forgery. After the full description was available he accepted that it was genuine and Mary Anning was vindicated and gained recognition as a valued source for fossils.

It was after this that Henry De la Beche (1796–1855), a friend of Mary Anning who had learned some geology from her, painted the now famous watercolour *Duria Antiquior* (Fig. 6, *overleaf*) . This depicted the imagined environment that could have existed in the Early Jurassic and resulted in the deposition of the Dorset Lias, and was based on the fossils that Mary Anning had collected there. De la Beche donated the proceeds of the illustration to Mary in recognition of her contribution to the scientific community. He later became the first professional geologist and head of the Ordnance Geological Survey, later the British Geological Survey.

Pterodactyl, *Dimorphodon macronyx*

The first example of a pterosaur was found in the Solnhofen limestones in Germany in 1784, the long thin bones indicating a bird-like creature that might have the ability to fly. Mary Anning found the first example outside Germany (Fig. 7, *overleaf*), although it was missing its head, and shared the knowledge of its discovery with Buckland. He announced the discovery to the Geological Society of London, naming the finder as Mary, and suggested the name *Pterodactylus macronyx*, meaning 'large clawed, flying dinosaur'. This was changed after Richard Owen (1804–1892), the first director of the Natural History Museum, London, found two further specimens and renamed the species *Dimorphodon macronyx* in 1859. Owen later named the Anning specimen the holotype and it is held by the NHM. The second specimen of this species that Mary found was in a better state of preservation and Buckland was able to persuade the NHM to purchase it for 100 guineas.

In 1863 Owen, as Superintendent of the Natural History department of the British Museum, was responsible for the purchase of the first specimen of Archaeopteryx, which is known as the London Specimen and is now held in NHM.

Figure 6 Duria Antiquior, watercolour painting made by Henry De la Beche in 1830 of an imagined landscape of the early Jurassic based on the fossils that Mary Anning found in the Dorset Lias (https://commons.wikimedia.org/wiki/File:Duria_Antiquior.jpg National Museum Cardiff, Public domain, via Wikimedia Commons; accessed 17-07-2021).

(An earlier version of this article was originally published in the Severnside Branch Newsletter Sabrina Times *September 2021 — Editor.)*

Sources

Buckland, William, Pickering, William, and Whittingham, Charles 1836 *Geology and Mineralogy Considered with Reference to Natural Theology*. London: Bridgewater, *Treatises on the Power, Wisdom, and Goodness of God, as Manifested in the Creation* **6**

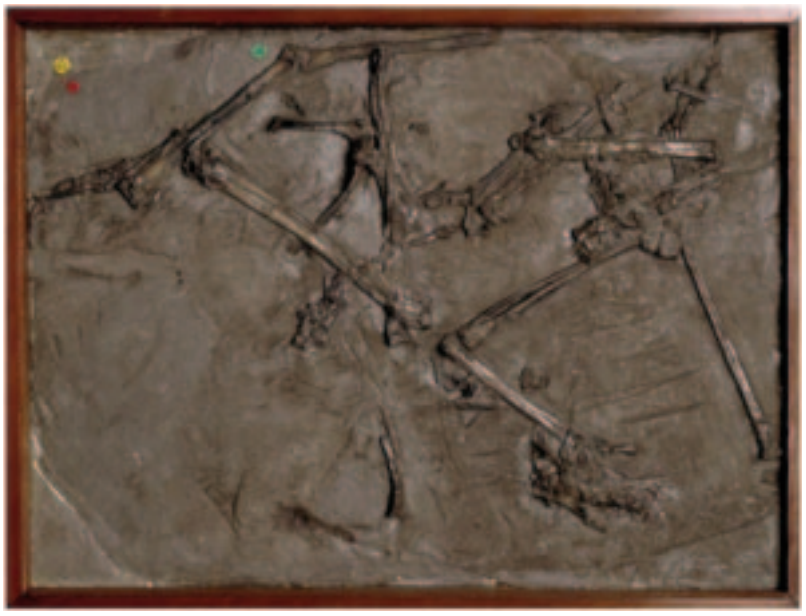
Davis, L. E. 2009 'Mary Anning of Lyme Regis: 19th century pioneer in British Palaeontology'. *Headwaters* **26**, 96–126

Home, Sir E. 1814 'Some account of the fossil remains of an animal more nearly allied to fishes than any of the other classes of animals'. *Philosoph Trans Roy Soc* **104**, 571–7 and plates 17–0

National Archives website Currency Converter 1270-2017: https://www.nationalarchives.gov.uk/currency-converter/#currency-result (accessed 19-07-2021)

Torrens, H. 1995 'Mary Anning (1799-–847) of Lyme; "the greatest fossilist the world ever knew"'. *Brit J Hist Sci* **28**, 257–84; doi: 10.1017/S0007087400033161

Figure 7 Dimorphodon macronyx *holotype found by Mary Anning and held at the Natural History Museum: https://www.nhm.ac.uk/discover/mary-anning-unsung-hero.html (accessed 19-07-2021)*



Marie Tharp and the mystery of drifting plates

Colin Morley

Introduction

July 2020 was the centenary of the birth of Marie Tharp, whose work led directly to the acceptance of plate tectonics as the true working of Earth's plate movements. The speculation that continents might have 'drifted' was first put forward by Abraham Ortelius in 1596. It was not until 1912 that the concept was independently and more fully developed by Alfred Wegener, but his hypothesis was rejected by many for lack of any explanation of a mechanism to cause the movement (Fig. 1).

The geoscientific community finally accepted plate-tectonic theory after seafloor spreading was validated in the late 1950s and early 1960s by Marie Tharp. She was a geologist and oceanographic cartographer who, with Bruce Heezen, created the first scientific map of the Atlantic Ocean floor.

Tharp and Heezen's Atlantic Ocean floor map was in widespread use in universities to teach the new generations of geologists and oceanographers, but her name was not widely known. The qualities of the map were such that established geologists and students alike were better able to understand the temporary and shifting nature of plate boundaries. The researchers of the time were now able to envisage the past plate tectonic setting of their own field study areas. With the aid of this map, visualising plate tectonics became so much easier, for the wider public as well as academia. Non-specialists could 'see' the shape of the ocean floor and the structure of the ocean basins. It was no wonder this map had an immediate and widespread impact.

Echo-sounding ocean traverses

'Floor of the Oceans' by Heezen, Tharp and Ewing, published in 1959 (Heezen, Tharp and Ewing 1959), was the first of a projected series of diagrams. The series was to be based on continuous echo-sounding traverses made by research vessels. The relief shown on the profiles was sketched in perspective using the technique introduced by Armin Kohl Lobeck, a Cartographer, Geomorphologist and Landscape Artist also at Columbia University with Heezen and Tharp, and Marie liked his style of presentation.

Between sounding profiles the relief is speculative, based on extrapolation of trends noted in the profiles. Marie Tharp was given the job of using all these plots to produce a graphical representation in the form of a map. The map of the entire ocean *floor — The Floor of the Oceans* topographical map— was published in late 1977 and Bruce Heezen's name was first author because Marie Tharp was not well known. All of the other map projections of the Atlantic, etc in the years between the 1959 publication and the 1977 publication of the full map did not have Marie's name on them!

The work caused some key figures in the history of plate tectonics to change the direction of their research. In late 1977 The Floor of the Oceans topographical map was published, and this time the authors credited were Bruce Heezen and Marie Tharp. Clearly, Tharp had been affected by the age-old idea that a female could not possibly be the person that discovered this, so it was not until the 1990s that she began to be recognised nationally and internationally, and receive awards for her work.

Figure 1 Marie Tharp with Bruce Heezen and their map of the Atlantic Ocean floor (Marie Tharp Maps CC BY 2.0 via Flickr).

Tharp's early studies

Marie Tharp initially got what could be called a 'liberal arts' degree, with some German, botany, drafting, art and an introduction to earth sciences. Later, during WWII, she gained another degree, and with it came a job with an oil company. She later earned a Master's degree and began work with Maurice Ewing's geophysics team at Columbia University in 1948. To put this achievement in perspective, 1948 was the year that Cambridge University decided to begin granting degrees to women.

Maurice Ewing (1906–74) trained as a physicist and was encouraged to apply his land-based geophysics to study sediment thicknesses on the continental shelf off eastern North America. He acquired funding and ship-time from the Navy, who saw strategic value in his work. He and his graduate students, including Tharp, had to build the equipment they needed for underwater seismic investigations and photography. The instruments being developed for military purposes were also useful for carrying out scientific investigations. Ewing quickly became a well-known name in the emerging discipline of geophysics. He took on Bruce Heezen (1924–77), fresh from his undergraduate degree, as chief scientist and ocean expedition leader. Tharp, although older and more qualified, was not considered for such roles. She reports working long hours along with the men, but women were not allowed to go on expedition ships and she was left out of the stimulating daily research meetings.

The ocean floor map

In the spring of 1952, while her colleagues were away at a conference in Brussels, Tharp, feeling the injustice of her situation, left Columbia University and headed back to her father's farm to do some thinking. Her absence was felt strongly and highlighted the importance of the contribution she was making to the team.

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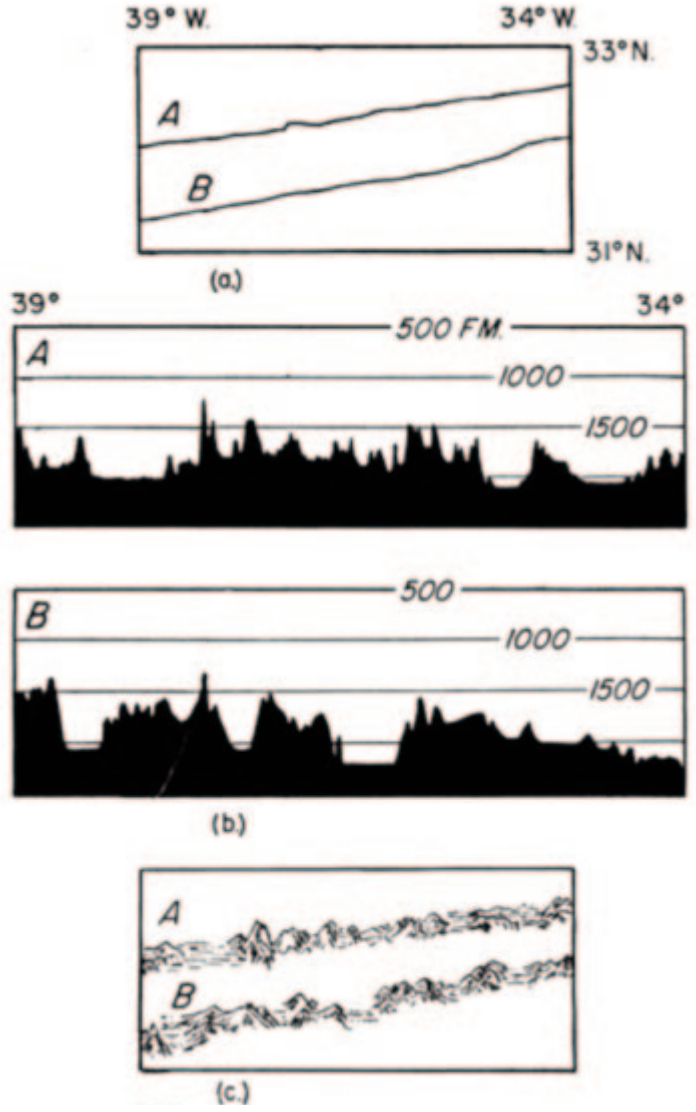
As evidence of this, Ewing changed the set-up in order to attract her back. He organised for Bruce Heezen to oversee her workload.

Soon after Tharp's return, Heezen decided that she should work solely with him, and this new arrangement began a highly productive partnership that endured all of their lives. By this time Heezen had gained his Master's degree with a thesis on the Grand Banks, where underwater communication cables were susceptible to breakage and had been damaged following the 1929 earthquake. He had been able to show that unstable sediment, moving rapidly under gravity, was breaking the submarine cables. From the communications company, Heezen knew exactly the time and location of each cable break, which enabled him to predict the existence of what he called 'turbidity currents' and to calculate their speed off the Grand Banks. It was a really good geological detective story and it found its way into many undergraduate degree courses.

Heezen, who became well known for this work, gave Tharp a massive dataset of paper-based depth profiles, known as fathograms, that had been collected over the previous decade. A fathogram was a continuous roll of paper tens of metres long representing depth soundings that had been taken routinely and continuously as exploration ships zigzagged across the continental slopes and ocean basins. There were many, many fathograms and Tharp had to figure out how such a huge dataset could be meaningfully represented. The ship's track needed to be accurately matched with the depth profiles. The illustration in Figure 2 shows Marie Tharp's mapping process. The top chart (a) shows the position of two ship tracks (A, B) moving across the surface. The two graphs below that (labelled (b)) plot depth recordings made by A and B as profiles, exaggerating their height to make features easier to visualise. The bottom chart (c) sketches features shown on the profiles.

Figure 2 Method of preparation of physiographic diagram (Heezen, Tharp and Ewing 2015).



Tharp began with the North Atlantic datasets. Many calculations and corrections had to be made from the raw data. She created profiles into six complete sections crossing the ocean. She plotted these at very large scale, with large vertical exaggerations, and then aligned the profiles from north to south. She saw that each profile had a deep notch at the crest of the mid-ocean ridge, and that these notches lined up. She checked and double-checked, but knew she had discovered something new and she gave this linear feature the name 'rift' with the implication of a tensional origin. It was then autumn 1952.

The reaction of the rest of the team, including Heezen, was not surprising — it was disbelief. Tharp's findings supported the hypothesis of continental drift and this went against the conventional geological teaching of the time. She was told to re-check all her figures and calculations. There was an entrenched anti-Wegener tradition at Columbia University.

Tharp re-checked and continued with the work, plotting the data as a map of the ocean floor. Crucially, she used specific topographical visualisation and presentation techniques that she had learned as a student. Once the known data were plotted in this way, there were large gaps of ocean without depth soundings. In spite of this, Tharp continued to add detail, and interpolated between existing profile lines. In this way, she produced the first physiographic map of the floor of the North Atlantic Ocean. In order to understand the data more thoroughly, Tharp and Heezen produced a well-known model of the Atlantic Ocean commonly called the 'basketball (bathymetric) model' (Fig. 3, *opposite*). It is in the Library of Congress in the USA. (Remember, the sort of modelling we do today using computers was not available at the time. Their work was all done on paper.)

Tharp and Heezen collaborated with the Austrian painter Heinrich Berann in order to produce their map of the entire ocean floor, which was published in 1977 by *National Geographic* magazine with the title 'The World Ocean Floor' (Fig. 4, *opposite*). Although today Tharp is recognised and given credit for her work on the Mid-Atlantic Ridge, it was Heezen who originally (in 1956) publicised and received credit for the discovery that was made.

Recognition of Tharp's work

After Heezen's death, Tharp stayed on the faculty of Columbia University until 1983, when she retired and started a map distribution business in her home town. She donated her entire map collection and notes to the Map and Geography Division of the Library of Congress in 1995. In 1997 the Library of Congress named her one of the four greatest cartographers of the 20th century and included her work in an exhibit in the 100th anniversary celebration of its Geography and Map Division. In 2001, Tharp was awarded the first annual Lamont-Doherty Heritage Award at

Figure 3 The 'basketball' globe (NOAA Photo Library map00318 via Wikipedia, CC BY 2.0 (background removed)).

her home institution for her life's work as a pioneer of oceanography. She died of cancer in Nyack, New York on August 23, 2006 at the age of 86.

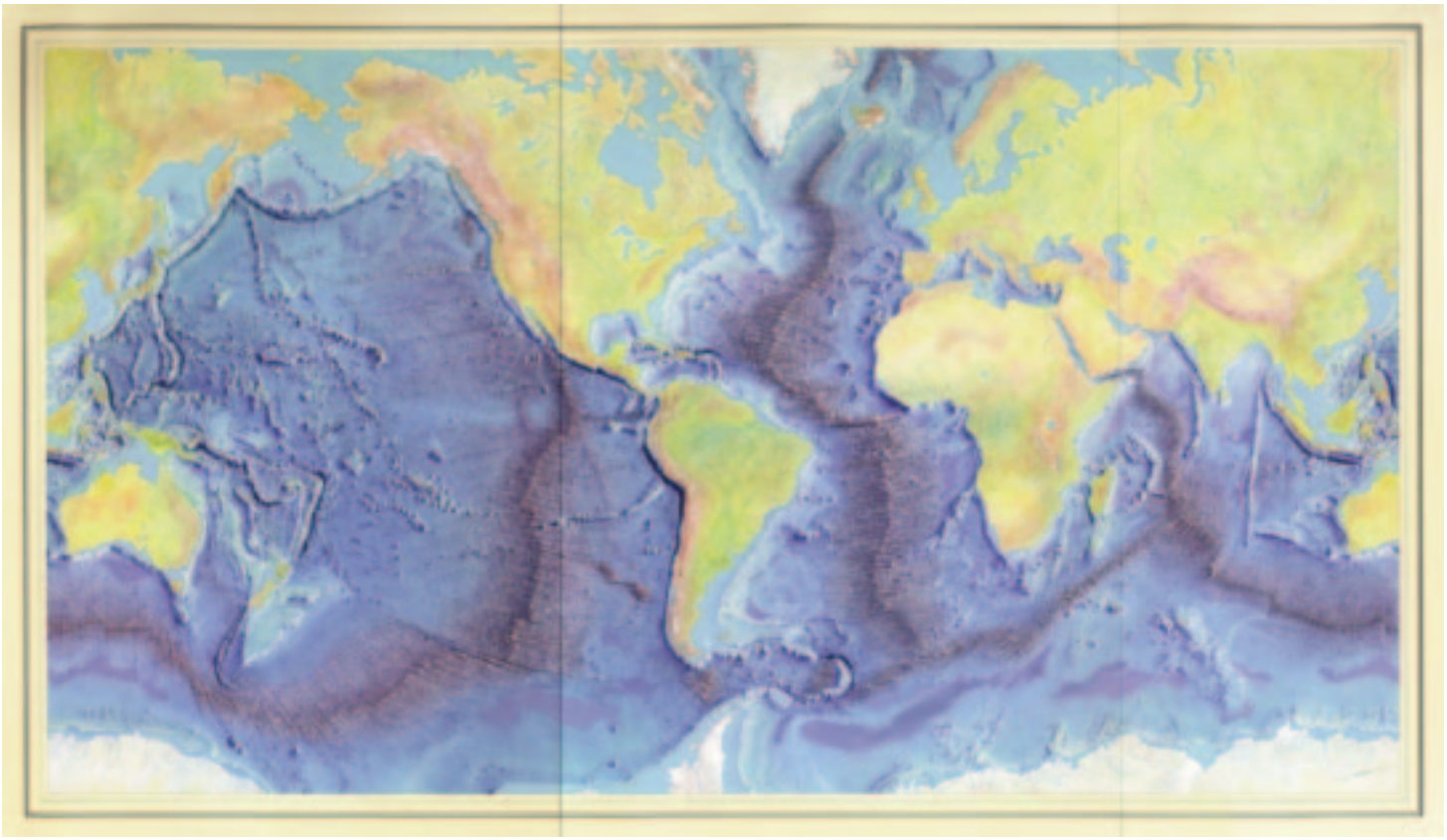
References

Heezen, B. C., Tharp, M., and Ewing, M. 1959 'The Floors of the Oceans: 1. The North Atlantic'. *Geol Soc America* 65, https://doi.org/10.1130/SPE65-p1

Heezen, Bruce D., Tharp, Marie, and Ewing, Maurice 2015 'The Floors of the Ocean: 1. The North Atlantic'. Text to accompany the physiographic diagram of the North Atlantic. Project Gutenberg EBook #49069 released 29 May 2015: https://www.gutenberg.org/files/49069/49069-h/49069-h.htm (accessed 23-03-2021)

(An earlier version of this article was originally published in the Wessex Branch Newsletter Footnotes *May 2021 — Editor.)*

Figure 4 Heinrich Berann's painting of the Mid-Ocean Ridges, 1977, by Tharp and Heezen (Public Domain).



Book review

Burek, C. V., and Higgs, B. M. (eds) 2021 *Celebrating 100 Years of Female Fellowship of the Geological Society: Discovering Forgotten Histories*. London: Geological Society Special Publication 506 (ISBN 978-1-78620-496-7; 302pp; hardback £95.00)

For anyone unfamiliar with the style of these Geological Society Special Publications they are not written in a traditional book format, but rather as a collection of scientific papers by different authors on a theme. I was vaguely aware of this, having flicked through a couple at events, but this is the first one I had read. So it did take a little adjustment to adapt to a different style and topic every few pages. The benefit of this style is that you can dip in and read one paper without having to worry about forgetting something you read in the previous chapter. This issue follows a publication by the same editors in 2007 entitled, *The Role of Women in the History of Geology*, which I have not read. So I cannot comment on their 2021 book with reference to the previous one. The original 2007 publication has been widely cited by geologists, sociologists and historians in papers and articles in several languages.

Professor Lynne Frostick, President of the Geological Society 2008–2010, wrote the Foreword. A chartered British geographer and geologist who has published more than one hundred papers and books, crossing disciplines including physics, mathematics and hydraulic engineering; Professor Frostick was appointed Commander of the Order of the British Empire (CBE) in the 2022 New Year Honours for services to flood risk and coastal erosion management.

The first female Fellows were elected to the Geological Society of London in 1919, 112 years after its founding in 1807, and this Special Publication celebrates the centenary. The first paper is an introduction by Burek and Higgs explaining that they aim to fill some gaps from the previous publication and focus on 20th- and 21st-century female geologists. For reference they have provided a table of the names of the women included in the publication from Margaret Cavendish Bentinck, Duchess of Portland (1715–1785) through to Kirsty 'Bang' Brown (1974–2003). Looking down the table the names of two of the authors immediately jumped out at me, our very own J. D. Mather and J. A. Bennett. The publication documents women who were in danger of being 'lost' to the history of geology, and while they acknowledge there will also be men who are at risk of being forgotten, they are not within the scope of this publication. Women working in academia and in the field, across the UK, Ireland, Finland, Russia, Australia, Africa and the USA are included with a variety styles from personal recollections to analyses written by geologists and historians. Each paper has been peer reviewed by at least two people. Before 1919 women were allowed to read their papers to The Geological Society at Burlington House, although most papers written by women were read out by men on their behalf, and allowed to use the GS library. But it took years of campaigning for women to gain the right to be nominated for Fellowship. On 21 May 1919 eight women were elected to become Fellows of the Geological Society.

Cynthia Burek's paper is a historical perspective on the awarding of medals and funds to women. Before WWII only four women had received GS medals: in 1919, 1920, 1932 and 1936. In the first 18 years of this century more awards have been made to women than in the previous 200 years. Burek explains the various medals and funds awarded by the Geological Society and their criteria.

Burek's second paper is a biography of the first woman to be elected as a Fellow in 1919, Margaret Chorley Crosfield, FGS.

'Ladies with hammers — exploring a social paradox in early nineteenth-century Britain' examines how the Industrial Revolution and the trend for less complicated dresses freed women of higher social standing from some of their traditional household duties and social restrictions to enable them to take up the fashionable hobby of geology. They collected fossils, helped their husbands, drew detailed scientific illustrations, painted landscapes, wrote popular science books and were generally considered very helpful, but had no access to formal education or resources until nearing the end of the century. King's College London barred women from Charles Lyell's lectures because they might distract the students from their studies. There were two formally registered male students at the time, plus some visitors. When the Royal Institution stepped in and asked Lyell to give a series of lectures he reckoned that of the approximately 250 people who attended each of the seven talks, no more than 100 at each were men. Considering that at the time to maintain their social status and respectability women had to be chaperoned by a suitable male to attend such events, I can only imagine groups of women organising which father, brother or husband would be flattered into attending which event.

The life and scientific collections of Eliza Gordon Cumming form the subject of the next paper. It looks at re-evaluating the amount of serious scientific work carried out by women such as Lady Gordon Cumming in forming their collections, which had been written off for years as a hobby, even when male geologists were using their work as a resource without acknowledging the women's contributions.

Consuelo Sendino, supported by Julian Porter, has investigated how female aristocrats used their wealth and influence to build world-class collections during the 18th and 19th centuries, before the establishment of the Geological Society of London. They give a brief biography, and describe details of the collections, the present whereabouts of these collections and the contribution to science of three women: Margaret Cavendish Bentinck, Duchess of Portland (1715–1785); Louisa Finch, Countess of Aylesford (1760–1832); and Anna Brassey, Baroness Brassey (1839–1887).

The roles of women in the Palaeontographical Society is the subject of the next paper. Although women were involved since its formation in 1847 they formed less than 10% of the membership in the early years and had no representation in the running of the Society. Women have been included for election to council since 1901, but there have only ever been four female vice-presidents and no female president for 175 years. Female authors still only account for less than 20% of articles published by the Palaeontographical Society. All things considered they are still a long way from female parity. This paper introduced a term I had never heard before: 'Steamboat Ladies'. This referred to women who, between 1904 and 1907, received their education at an English university, such as Newnham College, Cambridge, but were not allowed to graduate, so they travelled by steamboat across to Trinity College, University of Dublin to receive their degrees.

(continued on page 26)

Chalk (Clunch) Marks across Cambridgeshire

Philip Findlay

Introduction

Is there chalk in Kent? Yes, there are the white cliffs of Dover. Is there chalk in Sussex? Yes, there are the white cliffs of the Seven Sisters. Is there chalk in Cambridgeshire? Yes, there are the white fields of Cambridgeshire as shown in Figure 1. However, this view is from a satellite during that short time period when the produce has been harvested and the fields freshly prepared for the next crops. Viewed from ground level the presence of chalk in Cambridgeshire is not as immediately eye-catching as in some other counties.

This article does not contain detailed information about research concerning the geology of south Cambridgeshire: it is a summary about places visited where chalk, and in particular clunch, have left its marks in the southern parts of the county. The places visited are described in sequence travelling from east to west, from near the Suffolk border to the outskirts of Cambridge and then on to Steeple Morden near the neighbouring counties of Bedfordshire and Hertfordshire.

Figure 1 Fields near Burwell (Bing maps n.d.).

Clunch

The bedrock succession in south Cambridgeshire is shown in Figure 2. Towards the border with Suffolk the chalk ridge rises out of the fens and the younger Cretaceous beds then dip gently towards the south-east. Compared with rises of 200 m along the limestone ridge of the Cotswolds this 20 m ridge is low, but it still appears significant. Perhaps it is partly an illusion prompted in the east by the constant presence of the flat fens that stretch out to, and then along, the horizon. The chalk from south Cambridgeshire has long been the raw material for the production of lime for mortar and for agricultural use. Chalk is typically soft. Although chalk's main mineral component, calcite, has a Mohs Scale hardness of 3; and owing to its structure, chalk itself has a hardness of only 1 (Compare Rocks n.d.). It is permeable. When absorbed moisture near the surface freezes, the chalk's outer layers flake off. In spite of these inherent disadvantages chalk remains an important substance for modern buildings and construction works through its use as a raw material in the production of cement.

Group	Subgroup	Formation	Member (Average thickness =)	Age and Date (Ma)
Chalk	White Chalk (previously Middle and Upper Chalk)	Holywell Nodular Chalk (25 to 35m)		TURONIAN 93.9
			Melbourn Rock (2 to 7m)	
			Plenus Marls (1.0 to 1.5m)	
	Grey Chalk (previously Lower Chalk)	Zig Zag Chalk (35 to 50m)		CENOMANIAN
			Totternhoe Stone (1 to 2m)	
		West Melbury Marly Chalk (15 to 25m)		
			Cambridge Greensand (0.1 to 1.0m)	100.5 ALBIAN
Selborne		Gault		

Figure 2 Bedrock succession across the Cambridgeshire chalk ridge (BGS a and BGS c).

Clunch, a harder and stronger chalk than most, has been used unprocessed as a building stone. Totternhoe Stone, in a bed typically 1 m to 2 m thick, but in Cambridgeshire reaching a maximum of *c.* 7 m in the Swaffham Prior area, is probably the most well known clunch (Fig. 2). It is a fine-grained calcarenite with a high proportion of small shell fragments. The location of Totternhoe Stone across South Cambridgeshire is shown in Figure 3, with younger Cretaceous beds at the surface to the south-east and older ones to the north-west.

If the map shown in Figure 3 was extended to the south-west then the Totternhoe Stone bedrock trace would be seen to run just to the north of Luton and Dunstable before passing through the Bedfordshire village of Totternhoe that gives its name to the stone.

Figure 3 Map of Totternhoe Stone bedrock across South Cambridgeshire (BGS b).

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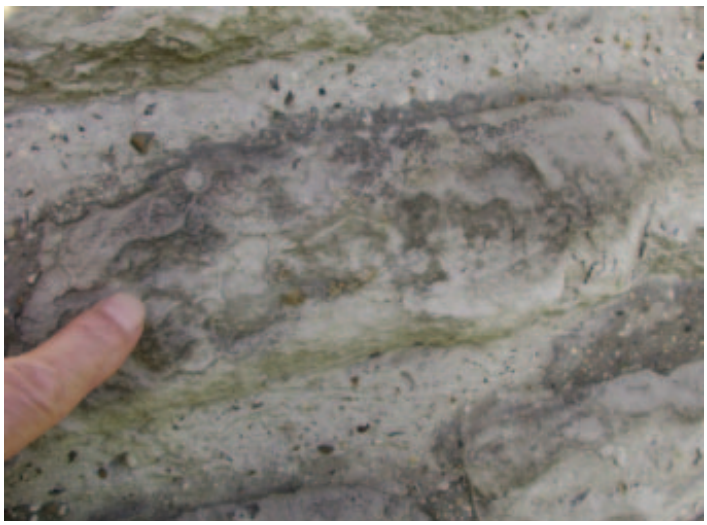


Figure 4a (left) Priory Church, herringbone pattern; 4b (right) Priory Church, clunch block.

Isleham

In Isleham near the Suffolk border, at the eastern end of the map shown in Figure 3, the Priory Church, built early in the 12th century, has lots of clunch in its walls (English Heritage). In places, thin blocks have been laid in herringbone patterns (Fig. 4a). Larger blocks in the walls show the fine-grained texture and grey-white colour of the clunch (Fig. 4b).

There is evidence that clunch was already being quarried in Isleham from the 11th to 12th centuries, so the clunch in the Priory Church walls may not have travelled far (Newton 2010). In later years, the softer chalk was converted to lime in lime kilns built within the Isleham quarries. One set of lime kilns (TL 64389 74202) in use from 1860 until 1935 is still standing on the quarry floor (Isleham Lime Kilns n.d.) (Fig. 5a). The quarry itself has also stopped working and bats have taken up residence inside the lime kilns. A public notice appeals for the bats to be left undisturbed. In fact, the whole of the old quarry has become a residential area, as it is now filled with houses making up what is now named Limestone Close. White chalk quarry walls, further reminders of the area's past identity, are on show at the bottoms of the gardens (Fig. 5b).

To help make the clunch used in external walls more weather resistant the surface is often painted with lime wash, but this needs to be re-applied periodically. A clunch wall alongside Mill Street, the main street in Isleham, shows both the lace-like remnants of a white lime wash coating and also the grey-white clunch blocks, weathered and crumbled, where the lime wash coating has deteriorated (Fig. 6, *opposite*).

Totternhoe Stone and the younger chalk above it are permeable, but the West Melbury Marly Chalk below the Totternhoe Stone is not. In places along the chalk ridge, water that has accumulated in the chalk above emerges as springs at the bottom of the Totternhoe Stone. The existence of these springs as well as the access to clunch that could be used for buildings may have been important factors in the early establishment of the communities that have grown up along the Totternhoe Stone bedrock line (*see* Fig. 3).

Burwell

Burwell is one of these communities. The earliest known record of 'Burwell' used as a place name is from the year 1060 (East Cambridgeshire District Council 2012). The name means 'fort' or 'fortified village by the spring' (East Cambridgeshire District Council 2012). The name was already in use before 1143, when under the orders of King Stephen of England the building of a castle next to the springs was started but never finished. Today the ruins of that building site lie over a wide area and the ruins themselves in turn sit on top of the ruins of a Roman building (Historic England a).

Figure 5a (left) Old quarry floor lime kilns, Isleham; 5b (right) White chalk quarry wall behind houses in Limestone Close in the old quarry, Isleham.

Figure 6 Clunch wall with residual traces of a lime wash coating.

The springs and the castle ruins are in a field along the side of which runs the appropriately named 'Spring Close'.The springs (TL 58866 66057) emerge on the eastern edge of the field at the foot of the chalk ridge that climbs less than 10 m from the springs to the nearby Church of St Mary. The harder, lumpy chalk, the Totternhoe Stone, is visible among the vegetation surrounding the springs (Fig. 7). This lumpy appearance of the Totternhoe Stone may be an explanation for the stone acquiring the name 'clunch'. Arkell and Tomkeieff (1953) suggest the name was probably from the adjective 'clunch' meaning 'lumpy; heavy and stiff or close', while the Oxford English Dictionary suggests the origin was perhaps from the use of 'clunch' in dialogue meaning 'lumpy, thickset' (Stevenson and Waite 2011).

Totternhoe Stone has to be cut and shaped before it dries and hardens. It tends to shatter if it is worked once it has dried out (Bedfordshire and Luton Geology Group n.d.). The Totternhoe Stone from the Burwell quarries was particularly valued for its high quality and was widely known as Burwell Rock or Burwell Stone; and Burwell itself was an important clunch production centre for Cambridgeshire (Huett 2014). The last clunch quarry in Burwell ceased working in 1962 (Huett 2014). As in Isleham, modern houses now occupy most of the old quarry floors; however, among the new homes one quarry corner (TL 59246 66188) has not been 'developed' and trees and bushes now grow there (Fig. 8).

Figure 7 Lumpy Totternhoe Stone at the spring line at Burwell.

Figure 8 Corner of old clunch quarry at Burwell.

The quarries in the village may have closed down, but the clunch extracted from them is still on display in many buildings and walls in Burwell. One of the most striking buildings is the Granary and Maltings, a Grade II listed building, at the south end of the village (Fig. 9a and b). The building's clunch walls rest on gault brick foundations. The main length of this late-18th century building has a thatched roof and, at the southern end, the malting

Figure 9a (above) The Granary and Maltings building;
9b (below) The malting kiln.

Figure 10 The Devil's Dyke looking towards the south-east.

kiln has a tile roof (Granary and Maltings …). Purcell (1967) wrote that clunch walls "protected by a good overhang to the roof and raised on a sound brick base" would last for many generations and the walls of this building have done so. Purcell made use of the same analogy as Loudon who in 1835 writing about cob walls declared that their durability depends upon "a good hat and a good pair of shoes" (Loudon 1835).

Reach

The village of Reach, like Burwell and several other villages near the Cambridgeshire chalk ridge ,such as Swaffham Bulbeck and Bottisham, is connected across the Fens to the River Cam by a lode, an artificial waterway. From the village, Reach Lode runs for almost 5 km to the north-west where it joins the River Cam at Upware. In the opposite direction, starting from the village and then covering more than 10 kilometres to Woodditton, run the ditch and chalk rampart of Devil's Dyke, built as a defensive barrier against incursions from the south-west (Cambridgeshire County Council 2013) (Fig. 10). The Devil's Dyke construction dates from the 6th or 7th century (Cambridgeshire County Council 2013) and the whole length is now a SSSI for its chalk and clay earth habitat (Natural England b). Reach Lode, possibly dating from the late Roman period, made Reach an important port from the 14th century for the export of clunch. The clunch, Totternhoe Stone, was extracted from the pits dug into Reach Hill on the edge of the village. The last cargo of clunch carried from Reach along Reach Lode left in the 1930s (Inland Waterways Association n.d.). Aucellina coquandiana specimens from Reach are among the Totternhoe Stone fossils on display at the Sedgwick Museum of Earth Sciences in Cambridge (Fig. 11).

Figure 11 Fossils from Reach.

Clunch Pit Lane leads from Reach to the old clunch pit area, which is now a developing woodland. On one November day in 1994 local volunteers planted 3200 trees here to create a new woodland in England's least wooded county (Wild Reach n.d.).

Figure 12 Clunch wall and St Mary's Church, Swaffham Prior.

The Swaffhams

Swaffham Prior and Swaffham Bulbeck are neighbouring villages both lying on the chalk ridge. At Swaffham Prior the High Street lies on the Totternhoe Stone, but there has been no extensive quarrying of the stone in the village. St Mary's Church sits on a terrace in the slope of the chalk ridge and below it a clunch wall borders the High Street (Fig. 12).

At Swaffham Bulbeck, there was a quarry from which Totternhoe Stone, as well as softer chalk, was extracted. A field now covers part of the old excavation area at the corner of Quarry Lane. Clunch was used to build much of the village church, the Church of St Mary the Virgin, including the West Tower (Historic England b). The area of the village next to the Swaffham Bulbeck Lode is still called Commercial End. The clunch blocks in a high wall (TL 55630 63490), alongside the road leading to the lode, display an extensive array of relatively young trace fossils (Fig. 13).

Lode

The aptly named village of Lode lies at the southern end of Bottisham Lode. The foundation stone of

Figure 13 Clunch wall with "trace fossils" at Commercial End, Swaffham Bulbeck.

Figure 14 Church of St. James, Lode.

the Church of St James in Lode was laid in 1852. Clunch was used for the walls of the church (Fig. 14). A side chapel was built in the 1960s and consecrated in September 1962. Clunch from Burwell was used to build the walls of this chapel (Pratt 2019). As mentioned earlier, the last of the clunch quarries in Burwell ceased working in 1962, so the blocks of Burwell Rock in the walls of this chapel (Fig. 15) are possibly among the last to be sourced from Burwell itself.

Cherry Hinton and East Pit

The chalk ridge passes along the edge of Cambridge through Cherry Hinton. Here, at the foot of a slope alongside the crossroads

Figure 15 Side chapel at Church of St James.

Figure 16 Cherry Hinton spring.

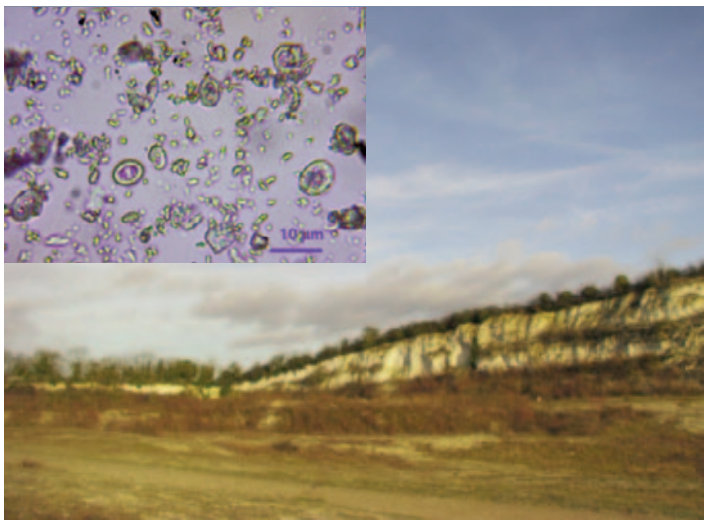
by the Robin Hood public house is the source of the Cherry Hinton Brook. A spring (TL 48538 56197) feeds water from under the Totternhoe Stone and the water moves away, flowing around the Giant's Grave island (Fig. 16). Perhaps this spring was the source of water for a nearby Iron Age settlement, traces of which have been found on what is now called Lime Kiln Hill (Pickstone and Mortimer 2012). A short walk up Lime Kiln Road leads to the East Pit (Fig. 17). The extraction of chalk from this pit stopped in the early 1980s and the pit is now a local nature reserve (The Wildlife Trusts b). None of the Cherry Hinton quarries that once supplied chalk for the lime kilns of Lime Kiln Road are still active.

On a sunny day, if you are standing in the middle of the East Pit, with the glare from the surrounding white quarry faces dazzling and forcing you to squint and shield your eyes, it can be difficult to think about the local, let alone the global, scale of accumulation of the microscopic calcium carbonate particles contained in the chalk. Microscopic examination of chalk dust from the East Pit reveals intact coccoliths among the calcium carbonate particles (Fig. 18).

The upper levels of chalk extracted from the East Pit belonged to the Holywell Nodular Chalk Formation. Changes in the material deposited during the formation of the chalk in East Pit produced two thin coloured bands, the older one red and the

Figure 17 (below) East Pit local nature reserve.

Figure 18 (inset) Coccoliths in East Pit chalk dust ×400.



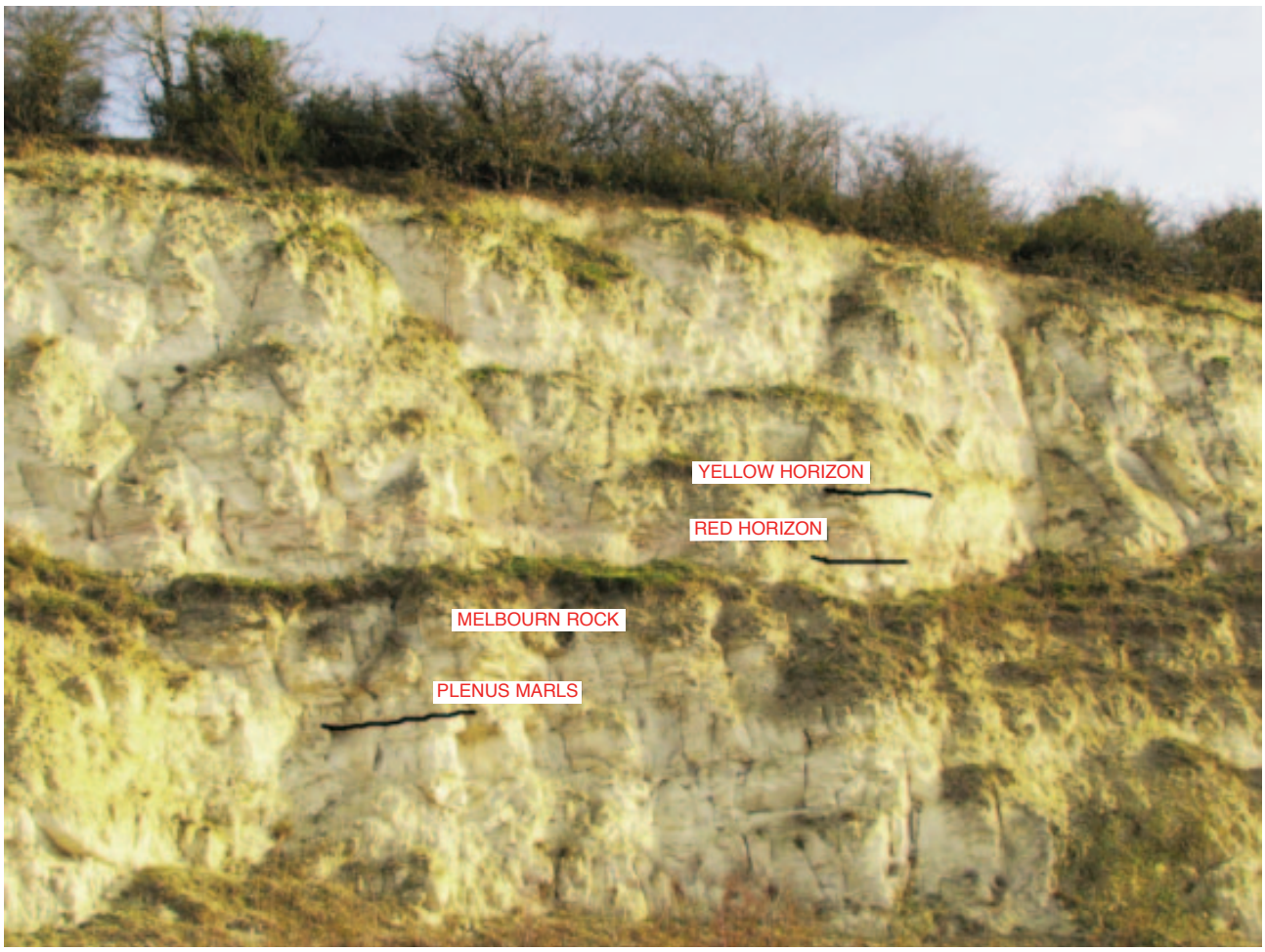


Figure 19 Rock in East Pit chalk face.

younger one yellow. These coloured bands provide an opportunity to identify several parts of the rock sequence shown in Figure 2 (The Wildlife Trusts a) (Fig. 19).

Nine Wells and Hobson's Conduit

The Cherry Hinton spring was bought by Cambridge University and the Town Waterworks Company in 1852 to supplement the supply of fresh water to the city of Cambridge (Bullivant 2008). An earlier supply of fresh water for Cambridge came from the cluster of springs also emerging from below the Totternhoe Stone farther along the chalk ridge at Nine Wells. A channel, named Hobson's Conduit after one of the benefactors, was constructed in 1610 to carry the spring water to flush out the stagnant water in Cambridge's ditches and separately to provide a source of fresh water. An obelisk (TL 46105 54113) was erected at Nine Wells in 1861 in recognition of the immense impact of Hobson's Conduit (Fig. 20). The open roadside channels in Cambridge, such as the runnels along Trumpington Street outside the Fitzwilliam Museum, are part of the Hobson's Conduit distribution network. Other parts of the network, such as along St Andrew's Street outside Christ's College, are now covered over, but marked with metal plates next to the kerbstones (Fig. 21). The water from Hobson's Conduit ran into and helped clean

Figure 20 The commemorative obelisk at Nine Wells.

Figure 21 Hobson's Conduit metal plate, outside Christ's College, St Andrew's Street.

the King's Ditch, a defence barrier that had become an open sewer, at what is now the junction of St Andrew's Street and Hobson's Street outside Christ's College. In comparison with those earlier times, today, with increased extraction of water from the aquifer, the flow of water from the springs at Nine Wells is much reduced.

Cambridge clunch

Having followed spring water from the Totternhoe Stone along Hobson's Conduit into Cambridge, it seems appropriate to also consider the use of clunch as a building stone within the city. In the 15th and 16th centuries, Cambridge colleges bought clunch from Burwell, Reche (Reach) and Hinton (Cherry Hinton), as well as from Barrington to the south-west of Cambridge (Purcell 1967). Today, clunch can still be seen in Cambridge: a clunch wall has been retained in Garret Hostel Lane (Fig. 22); clunch window surrounds survive in Trinity Lane (Fig. 23); and the 1615 clunch statue of Henry VIII is still standing in its niche in Trinity College Great Gate (Fig. 24). The clunch of the Henry VIII statue has survived longer than the metal sword the statue once held in the king's right hand. The sword had disappeared by the 1980s, possibly taken by climbing students, and was replaced with a wooden chair leg, which is still there, by two window cleaners, one anchoring the other as he stretched across from a nearby window to place the chair leg (Gray 2010).

Zig Zag Chalk and Robin Hood's arrow

Chapel Hill, south-west of Cambridge, is an outlier of Zig Zag Chalk. At the foot of the slopes of Chapel Hill, to the south, north and west, lie the villages of Barrington, Harlton and Orwell, all of which have their own clunch quarries on Chapel Hill, from which Totternhoe Stone was extracted. By far the largest quarry is at Barrington where the chalk was also used in cement production. Quarrying of chalk at Barrington stopped in 2008 and the site was closed in 2012 (Cemex Communities n.d.). As in the old quarries at Isleham and Burwell, houses are now being built on the floor of part of the old quarry. Totternhoe Stone from the Barrington pit can be seen in the walls of the Church of All Saints in Barrington village (King and Collins 2019); and the white quarry faces left in the side of Chapel Hill at Barrington are still visible from 15 km away at Steeple Morden (Fig. 25).

Figure 22 Clunch wall, Garret Hostel Lane.

Figure 23 Clunch window surrounds, Trinity Lane.

Figure 24 Henry VIII statue, Trinity College Great Gate.

Figure 25 The white quarry faces at Barrington.

Figure 26 Harlton Clunch Pit as seen from Steeple Morden.

Figure 28 St Andrew's Church, Orwell.

At Harlton and Orwell, the old clunch pits are much smaller than the quarry at Barrington and now each pit is owned by its local village. Lumpy chalk is still exposed on the steep sides of the old pit (TL 39076 52074) at Harlton, which is now a small area of woodland (Fig. 26). At Orwell the clunch pit (TL 39396 50673) is an SSSI for the chalk grassland that has survived there and is now grazed by sheep (Natural England c) (Fig. 27). The clunch from the Orwell pit was used in the building of the tower and walls of St Andrew's Church alongside Fishers Lane in Orwell itself (Fig. 28).

At Litlington, in 1811, the name of one of the village inns was the 'Robin Hood and Little John'. The name arose from a local fable that Robin Hood had shot an arrow that landed in the village chalk pit (TL 31547 41702) and then the arrow grew into a thorn tree. The inn closed in 1910 (Baggs, Keeling and Meekings 1982). Perhaps in deference to the local fable, hawthorn now dominates the thicket that covers the old chalk pit (Fig. 29).

Holywell Nodular Chalk

The Station Road Chalk Quarry at Steeple Morden is still active, extracting chalk from the Holywell Nodular Chalk Formation. The quarried chalk is carried more than a kilometre on a covered conveyor belt to the processing works sited in a different chalk quarry, the Plantation Quarry, among woodland (Figs 30 and 31, *opposite, top*). Omya UK uses the chalk to produce whiting for paper, and fillers for use in paints, pharmaceutical products and UPVC window frames. The chalk is also used to produce food-grade calcium carbonates for the food industry (Omya UK n.d.).

The village of Guilden Morden lies north of its neighbour, Steeple Morden, but the parish of Guilden Morden stretches south to the west of Steeple Morden and on into the south-west corner of Cambridgeshire. In this corner, in sight of Ashwell in Hertfordshire, lies Ruddery Pit (TL 28490 40082), the old parish clunch pit of Guilden Morden (Fig. 32, *opposite*). The pit encroaches on an early Iron Age and Romano-British cemetery. During archaeological excavations in 1936, finding that later burials in the cemetery often reused the sites of earlier burials led the Director of Excavations, Thomas Lethbridge, to suggest that it was a practice "done to save the trouble of digging more hard, undisturbed chalk than was necessary" (Lethbridge 1936).

More springs and rivers

The River Cam flows roughly in a north-east direction through the southern part of Cambridgeshire to join the River Great Ouse near Ely. To the west from Ruddery Pit, less than a kilometre over the Cambridgeshire border into Hertfordshire, alongside the High Street in Ashwell, a series of springs (TL 27013 39783) provides the source water for one of the main tributaries of the Cam — the River Rhee. As in other places already mentioned along the chalk ridge, the spring waters emerge from the junction between the

Figure 27 Orwell Clunch Pit.

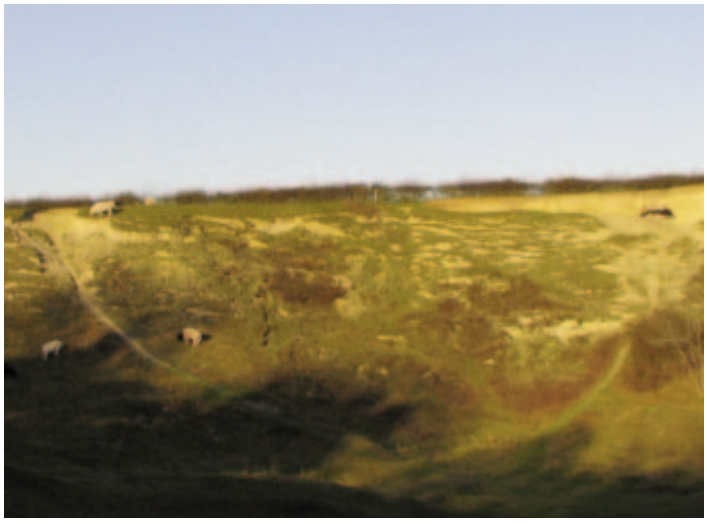


Figure 29 Litlington old chalk pit.

Figure 30 Chalk processing works, Steeple Morden.

Figure 31 Conveyor belt running between the quarries.

Totternhoe Stone and the West Melbury Marly Chalk (Fig. 33). The area in Ashwell where the springs rise is a SSSI (Natural England a), as the springs provide cold water at an almost constant temperature, never greater than 12° C, for a glacial relict population of flatworms (Ashwell Parish Council). Crenobia alpina, one of the species of flatworms still found at Ashwell, used to be found in the water near the springs at Nine Wells, but, since the drought of 1976, are present no longer (MacCallum 1986).

Conclusion

Cambridgeshire, but not the Totternhoe Stone, ends at the county border along the approach road to Ashwell. After John Burroughs visited England in the 19th century he wrote: "England is not a country of granite and marble, but of chalk, marl, and clay" (Burroughs 1896). He was right about the marble; he did not visit the West Country and his visit to what he called 'Wordsworth's Country' focused on Helvellyn so his comment about granite is understandable: his overall summary was an excellent one for Cambridgeshire.

References

Arkell, W. J., and Tomkeieff, S. I. 1953 *English Rock Terms: Chiefly as used by Miners and Quarrymen*. London: Oxford UP, 26

Ashwell Parish Council *The Springs*. Public Information Board at Ashwell Springs

Baggs, A. P., Keeling, S. M., and Meekings, C. A. F. 1982 'Parishes: Litlington', *in* Wright, A. P. M. A *History of the County of Cambridge and the Isle of Ely.* London: Victoria County History **8**, 54–66; https://www.british-history.ac.uk/vch/cambs/vol8/pp54-66 (accessed 12-12-2019)

Bedfordshire and Luton Geology Group n.d. *Bedfordshire's Geological Industries: Totternhoe Stone.* http://www.bedfordshiregeology-group.org.uk/leaflets/BLGGTotternhoeStone.pdf (accessed 04-12-2019)

BGS a *BGS Geological Timechart, 'Cretaceous*'. https://www.bgs.ac.uk/discoveringGeology/time/timechart/phanerozoic/cretaceous.html (accessed 03-12-2019)

BGS b BGS Geology of Britain View. http://mapapps.bgs.ac.uk/geologyofbritain/home.html (accessed 03-12-2019)

BGS c *BGS Lexicon of Named Rock Units*. https://www.bgs.ac.uk/Lexicon/ (accessed 03-12-2019)

Bing maps n.d. https://gridreferencefinder.com/bing.php (accessed 30-11-2019)

Bullivant, M. 2008 'Brief history of Spring Head/Giants Grave, Cherry Hinton'. Cherry Hinton: Cambridgeshire Community Archive Network: https://cherry-hinton.ccan.co.uk/content/catalogue_item/ brief-history-of-spring-head-giants-grave-cherry-hinton (accessed 10-12-2019)

Burroughs J. 1896 *Fresh Field*s. Cambridge, MA: The Riverside Press 27

Cambridgeshire County Council *2013 Earthworks Way and Devil's Dyke Walks* (5th edn). https://www.visitcambridge.org/dbimgs/EarthworksWay(1).pdf (accessed 08-12-2019)

Figure 32 Ruddery Clunch Pit.

Figure 33 One of the springs at Ashwell.

Cemex Communities n.d. 'Barrington Community Matters'. http://www.cemexcommunities.co.uk/barrington.aspx (accessed 10-12-2019)

Compare Rocks n.d. 'Properties of Chalk'. https://rocks.comparenature.com/en/properties-of-chalk/model-17-6 (accessed 29-02-2020)

East Cambridgeshire District Council 2012 *Burwell Masterplan: A Framework for the future development of Burwell*. https://www.eastcambs.gov.uk/sites/default/files/FINAL%20burwell%20masterplan-web%20%282%29_0.pdf (accessed 04-12-2019)

English Heritage *Welcome to Isleham Priory Church*. Public Information Board at the Priory Church

'Granary and Maltings to Manor House: A Grade II Listed Building in Burwell, Cambridgeshire'. *British Listed Buildings*: https://britishlistedbuildings.co.uk/101126404-granary-and-maltings-to-manor-house-burwell#.XehK6Hk3bIU (accessed 05-12-2019)

Gray, R. 2010 'Mystery of Trinity chair leg revealed'. *Varsity*, Friday, November 5: https://www.varsity.co.uk/news/2757 (accessed 10-12-2019)

Historic England a *Burwell Castle*. https://historicengland.org.uk/listing/the-list/list-entry/1015596 (accessed 14-12-2019)

Historic England b *Church of St. Mary the Virgin*. https://historicengland.org.uk/listing/the-list/list-entry/1127052 (accessed 08-12-2019)

Huett, Bruce 2014 'What are Meldreth buildings made of? Wall and framework materials: clunch and claybat'. *Meldreth History: the Local History of Meldreth, Cambridgeshire*: http://www.meldreth-history.org.uk/page/what_are_meldreth_buildings_made_of-4?path=0p132p123p (accessed 19-11-2019)

Inland Waterways Association n.d. *Reach Port*. Public Information Board at the former site of Reach Port alongside Reach Lode

Isleham Lime Kilns n.d. Public Information Board at the Lime Kilns

Loudon, John Claudius 1835 *An Encyclopaedia of Cottage, Farm and Villa Architecture and Furniture*. London: Longman, Rees, Orme, Brown, Green and Longman, 417

King, A., and Collins, P. 2019 *A Building Stone Atlas of Cambridgeshire including Peterborough*. Historic England, Strategic Stone Study, 27

Lethbridge, T. C. 1936 'Further excavations in the early Iron Age and Romano-British cemetery at Guilden Morden'. *Proc Cambridge Antiq Soc* **XXXVI**, 110; https://archaeologydataservice.ac.uk/archiveDS/archiveDownload?t=arch-1895-1/dissemination/pdf/PCAS/1936_XXXVI/PCAS_XXXVI_1936_109-120_Lethbridge.pdf (accessed 12-12-2019)

MacCallum, F. 1986 'The natural history and conservation status of Nine Wells'. *Nature in Cambridgeshire* **28**, 50–3; https://www.natureincambridgeshire.org.uk/volumes/nature-in-cambs-vol-28-1986.pdf (accessed 06-02-2020)

Natural England a *Ashwell Springs SSSI*. https://designatedsites.naturalengland.org.uk/PDFsForWeb/Citation/1000593.pdf (accessed 12-12-2019)

Natural England b *Devil's Dyke SSSI*. https://designatedsites.naturalengland.org.uk/PDFsForWeb/Citation/1000404.pdf (accessed 05-12- 2019)

Natural England c *Orwell Clunch Pit SSSI*. https://designatedsites.naturalengland.org.uk/PDFsForWeb/Citation/1003869.pdf (accessed 10-12-2019)

Newton, Andrew A. S. 2010 'A medieval clunch-working site at Fordham Road, Isleham'. *Proc Cambridge Antiq Soc* (incorporating *Cambs and Hunts Archaeol Soc*) **XCIX**, 103–12; https:/archaeologydataservice.ac.uk/archiveDS/archiveDownload?t=arch-1895-1/dissemination/pdf/PCAS/2010_XCIX/PCAS_XCIX_2010_103-112_Newton.pdf (accessed 12-12-2019)

Omya UK n.d. 'White Minerals and Chemicals, Steeple Morden'. https://steeple-morden.cylex-uk.co.uk/company/omya-uk-white-minerals-and-chemicals-13000395.html (accessed 12-12-2019)

Pickstone, A., and Mortimer, R. 2012 'War ditches, Cherry Hinton: revisiting an Iron Age hillfort'. *Proc Cambridge Antiq Soc* **CI**, 3160; https://archaeologydataservice.ac.uk/archiveDS/archiveDownload?t=arch-1895-1/dissemination/pdf/PCAS/2012_CI/PCAS_CI_2012_031-060_ Pickstone_and_Mortimer.pdf (accessed 08-12-2019)

Pratt, M. B. 2019 *The Church of St. James Lode with Longmeadow*. Anglesey Group of Parishes, The Church of England; https://angleseygroupparishes.co.uk/parishes/lode/history/ (accessed 08-12-2019)

Purcell, D. 1967 *Cambridge Stone.* London: Faber and Faber Ltd, 28

Stevenson, A., and Waite, M. (eds) 2011 *Concise Oxford English Dictionary*. Oxford: UP, 273

The Wildlife Trusts a *The Chalk Landscape*. Public Information Board at the foot of one of the chalk faces within the East Pit local nature reserve provides information about the coloured bands and the adjacent rock sequences

The Wildlife Trusts b *Cherry Hinton Chalk Pits*. https://www.wildlifebcn.org/nature-reserves/cherry-hinton-chalk-pits0 (accessed 19-12-2019)

Wild Reach n.d. https://www.wildreach.co.uk/wildlife-resources/reach-wood/ (accessed 08-12-2019)

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An exposure of brockram at Rougholme Point, south Cumbria

Duncan Woodcock

Introduction

The geology of much of south Cumbria comprises Carboniferous Limestone that unconformably overlies the older Lower Palaeozoic rocks making up the core of the Lake District. These limestones are well exposed at several coastal locations. One such locality, at Humphrey Head (Fig. 1) comprises an east-dipping sequence of Asbian and Brigantian limestones that form a prominent ridge, some 50 m high, which extends southwards into Morecambe Bay. The west side of Humphrey Head falls sharply to an area of salt marsh that has been partly reclaimed for agriculture. Rougholme Point is a prominent raised area, *c.* 250 m long by 100 m wide, within the salt marsh, *c.* 500 m to the west of Humphrey Head. This area displays excellent exposures of Permian breccias and conglomerates known as 'brockram' (Fig. 2).

The juxtaposition of these early–mid Permian rocks against the Carboniferous rocks of Humphrey Head is due to movement along the NNW–SSE trending Humphrey Head Fault. This fault, with a downthrow of *c*. 1000 m to the west, resulted in the development of a half-graben within which the Permian rocks accumulated (Johnson and Soper 2001). The location of the Humphrey Head Fault coincides closely to the western edge of Humphrey Head, although the present-day steep slope is probably the result of the differential erosion of the more resistant limestones compared to the less resistant Permian rocks.

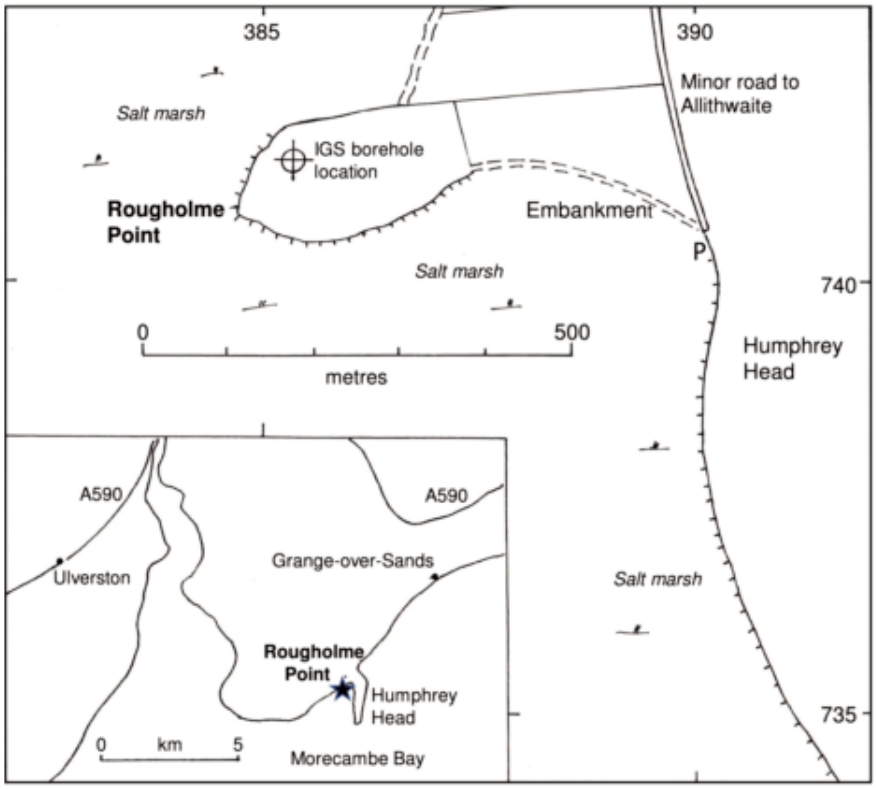

Figure 1 Sketch map showing the location of Rougholme Point, immediately west of Humphrey Head, south Cumbria. It is possible to park at the end of the minor road (P on map) and walk along the embankment to the exposures on the south and west sides of Rougholme Point.

Description

A stratigraphic thickness of *c.* 10 m of brockram is exposed in low cliffs, 1–3 m high, around the southern and western sides at Rougholme Point (Fig. 3, *overleaf*). The brockram comprises a poorly sorted breccia and conglomerate, together with interbedded sandstones (Fig. 4, *overleaf*) and the occasional thin parting of micaceous siltstone. Locally there is evidence of erosion, with channels infilled by coarser deposits (Fig. 5, *overleaf*). Overall, the sequence dips at *c*. 6° to the south. In places the exposures show cross-stratification (Fig. 6, *overleaf*); measurements of foreset orientation indicates a paleocurrent direction towards 200° magnetic after correction for tectonic tilt.

Figure 2 The west side of the limestone ridge of Humphrey Head, seen across an area of salt marsh, from exposures of Permian breccias and conglomerates known as 'brockram' at Rougholme Point.

The clasts within the brockram are generally sub-angular to rounded, up to *c.* 100 mm in size and set in a matrix of red sandstone. Most of the clasts are pale grey-weathering limestones that have been dolomitised; this can be demonstrated in the field by a lack of effervescence when cold, dilute HCl is applied. In addition to the carbonate clasts there are smaller, darker grey clasts of chert. Both carbonate and chert clasts were probably sourced locally; Humphrey Head immediately to the east comprises both Urswick Formation (Asbian) and Alston Formation (formerly Gleasdon Formation, Brigantian) limestones; the latter containing chert nodules (Adams and Wadsworth 1993). Some of the carbonate clasts have distinctive hollow centres (Fig. 7, *page 25*). Adams and Wadsworth (1993) suggest that this is probably due to incomplete dolomitisation of a clast, which occurs from the outside inwards, and that the residual undolomitised calcite core was subsequently dissolved by meteoric fluids. Adams and Wadsworth (1993) speculate that dolomitisation was caused by an ingress of saline fluids derived from the Zechstein Sea.

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Figure 3 Brockram exposures at the south-west end of Rougholme Point show a wide range of clast sizes that attest to rapidly changing depositional environments (walking stick c. *1 m long).*

Figure 4 A wedge-shaped bed of sandstone within brockram.

Petrography

In thin section, the carbonate clasts appear somewhat featureless and devoid of any bioclasts. They consist of anhedral, interlocking crystals, typically 0.1 mm in size. There are occasional pore spaces that are lined with euhedral, rhomb-shaped crystals that are characteristic of dolomite.

A thin section made from material taken from a coarse pebbly sandstone interbed contains small, angular carbonate clasts with a similar appearance to those described above. In addition, there are a few smaller microcrystalline clasts that are probably cherts. The sandy matrix comprises subangular to rounded quartz grains, typically 0.3–1 mm in size, with red-brown haematitic rims. The quartz grains are generally monocrystalline and show varying degrees of undulose extinction; some of the larger grains are polycrystalline. In addition, there are a few opaque grains that are generally smaller than the adjacent quartz grains. There is a fine-grained carbonate cement between the grains.

The Humphrey Head Borehole

In 1973, the BGS (then known as the Institute of Geological Sciences[IGS]) drilled a borehole on the flat area of land immediately behind the coastal exposures at Rougholme Point. A descriptive log of the core recovered from this 272 m deep borehole, called the Humphrey Head borehole, despite its true location, is included in the report of boreholes drilled by IGS in 1973 (Institute of Geological Sciences 1974). The borehole penetrated a total of 257 m of conglomerate and sandstone, which the IGS assigned to the Appleby Group, although the lack of fossil remains meant that this early Permian age could not be confirmed.

Material recovered from the top 26 m was described as being very similar to the rocks exposed at outcrop, but contained in addition occasional weathered igneous clasts of olivine dolerite and vesicular basalt. This clast type was found to increase in abundance deeper within the borehole, where it became the predominant clast type below 150 m. Thin beds of fibrous gypsum, together with beds comprising "loose aggregates of crystalline gypsum and anhydride" were encountered below 200 m. Core recovered from the lowermost 15 m of the borehole comprised a reddened mudstone and siltstone containing plant fragments that allowed a Namurian age to be assigned.

The igneous clasts were subjected to a detailed study (Adams and Wadsworth 1993). If these igneous clasts were locally derived, they provide the only evidence for Carboniferous volcanic rocks in south Cumbria.

Figure 5 A small, local channel, eroded into finer grained deposits, has been infilled with coarser material.

Comparison with brockram in the Eden Valley

The Eden Valley comprises a NW–SE trending area of Permo-Triassic rocks, some 50 km long and 5–10 km wide, that is bounded on the north-east side by the Pennine Fault System. This major fault system was active during a period of NE–SW

Figure 6 A cross-bedded layer within brockram.

extension during the early Permian (Stone *et al.* 2010), resulting in rapid subsidence to the south-west and the development of a half-graben. The breccias and conglomerates that make up the early infill of this sedimentary basin were sourced from the developing fault scarp and deposited within alluvial fans. The tectonic situation in the Eden Valley was thus similar in some respects to that at Humphrey Head.

The resulting brockram deposits are exposed at several locations within the Eden Valley. The exposures at Hoff Quarry, immediately south of Appleby, will be familiar to those who participated in the Durham Summer School associated with the second level OU Geology course. Sadly, these exposures are now out of bounds, although the lateral equivalent strata crops out near by.

Extensive exposures of brockram occur in the banks of the River Eden within Stenkrith Park, immediately south of Kirkby Stephen. Farther upstream at Nateby there are good exposures of brockram above the east bank of the river, adjacent to the public footpath at NY 772 066. These look similar to the brockram at Rougholme Point, although the distinctive hollow carbonate clasts are absent. Thin sections of carbonate clasts from Nateby show that they are not dolomitised, but comprise bioclastic limestone containing crinoid, coral and brachiopod fragments together with complete foraminifera.

References

Adams, A. E., and Wadsworth, W. J.1993 'The Humphrey Head Borehole: evidence for Carboniferous vulcanicity and Permian dolomitization in the southern Lake District'. *Geol J* **28**, 159–69

Institute of Geological Sciences 1974 'IGS boreholes 1973'. *Rep Inst Geol Sc*i **74/7**, 23pp

Johnson, E. W., and Soper, N. J. 2001 'Geology of the country around Ulverston'. *Mem Brit Geol Survey*, Sheet 48 (England and Wales). London

Stone, P., Millward, D., Young, B., Merritt, J. W., Clarke, S.M., McCormac, M., and Lawrence, D. J. D. 2010 *British Regional Geology: Northern England* (5th edn). Keyworth, Nottingham: BGS

Figure 7 Detail of clasts within the brockram at Rougholme Point, Carbonate clasts with hollow centres were probably formed by incomplete dolomitisation of limestone with subsequent solution of the residual cores.

(continued from page 12)

Carl Thompson's paper on Maria Graham was so interesting that I have asked my branch to contact him to see if he would be willing to give a lecture. Maria was the wife of a sea captain who went with him on his voyages and was a well-known travel writer of the early 19th century. In 1824 she became the first woman to have a contribution published in *The Transactions of the Geological Society* when she wrote an account of her experience of the 1822 Chilean earthquake. Her observations and interpretations supported the 'Vulcanists' or 'Plutonists' against the 'Neptunists', which fed into the ongoing controversy before she was proved correct by later correlation. While in Chile, Darwin specifically visited the location she had described to see her evidence for his own eyes.

Women were allowed to attend public lecture series on geology run by the Museum of Irish Industry, Dublin (MII) from 1854 to 1867, and, importantly, they were allowed to sit the examinations at the end of the series to gain recognition of their studies. The papers of the highest scoring students were put forward for awards, and the only reason we know these women existed is because the award winners were carefully recorded. The highest-scoring student of all, with a huge 956/1000, was Margaret Swan in 1861. A lack of funding led to the closure of MII in 1867, and its educational responsibilities were transferred to the Royal College of Science in Ireland. The Royal College's first official female student was not registered until 1901, although women were allowed to attend lectures on an informal basis ,as proven by one of the professors marrying a student in 1895. But no records exist and these women were not allowed to register or sit examinations.

To expand on their previous (2007) publication, Cynthia Burek has researched and written biographies of two of the early female Fellows, about whom there was a dearth of information when the papers published in the 2007 volume were written. Dr Mabel Elizabeth Tomlinson (1893–1978) was nicknamed 'Doc Tom', a researcher and teacher. Tomlinson wrote the first Higher School Certificate syllabus for geology in the early 1940s and continued after her retirement to advocate teaching geology in schools. On her retirement from teaching, her position was filled by Geoff Brown, a name that should be familiar to OUGS members, and in 2005 the Tomlinson-Brown Trust was established in their honour. Isabel 'Ellie' Knaggs (1893–1980) was a pioneering mineralogist using X-ray diffusion to study crystal structure. When reference to her work omitted to credit her by name her boss wrote to Nature asking them to publish a note from him giving her due credit. Unfortunately her work was over-shadowed by a male scientist who published, in less detail, the year after her first paper; and as recently as 2005 he is still being cited as the discoverer of the tetrahedral bonding of carbon atoms in diamonds.

More biographies follow: on Gertrude Elles, Eileen Mary Lind Hendriks (1887–1978), Doris Livesey Reynolds (1899–1985), Dr Dorothy Helen Rayner FGS (1912–2003), Rosemary Hutton, and Marie Tharp.

Robbie Rice Gries presents 'Buried discoveries of early female petroleum geologists' by following the lives of five women over 100 years as innovators of oil-finding technology.

The Siberian diamond province is the focus of the next paper, about two women and how they found the Zarnitsa kimberlite pipe in 1954.

Far-flung female fellows look at the work of women across the world. I found it fascinating and would recommend it, but obviously, given the price and the specialised nature of the book, it will have a limited readership. As for myself, I want to get the previous volume now too!

— Helen Coombs, BSc Hons (Geosciences), OUGS Information Officer

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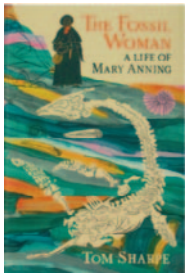
Book review



Sharpe, Tom 2020 *The Fossil Woman: a Life of Mary Anning* London: The Dovecote Press (ISBN 978-0-9955-4629-5; 240pp; hardback £20, paperback £12)

"She sells sea shells on the sea shore": contrary to popular belief, this tongue-twister is not about Mary Anning, but rather is a mid-19th-Century elocution exercise from Edinburgh. This is just one of the nuggets in this excellent biography, written by a geologist (and not by the novelist).

The Introduction begins with the August 2020 sale of a letter by Mary Anning to William Buckland, written in 1830.It sold for £100,000, some ten times the pre-sale estimate, thus highlighting the resurgence of interest in Anning over the last few years, following her retreat into the background after her death. Interestingly, no mention of her 'reconstruction' by an actress in the galleries of the Natural History Museum is ever made in the book. There are two pages of author's notes, which reacquaint us with £sd and imperial units, and then the story commences.

A medallion made for Anning's 11th birthday and found in 2014 now resides in Lyme Regis Museum. This takes us on to a description of Lyme Regis, a brief look at the surrounding geology and a discussion of fossils, their burial and preservation. A brief history of geology is given, along with the geological quartet most associated with Lyme Regis: the Williams Buckland and Conybeare, Henry De la Beche and Mary Anning herself.

Anning's early life is detailed in the next chapter, including her near miraculous escape from a lightning strike; and the following chapter details the two-part discovery of the first ichthyosaur from Lyme Regis, by her brother James (the skull in 1811) and Mary (the body in 1812). This was the first ichthyosaur to be scientifically described and named. Some interesting ideas were mooted as to what living creature it most resembled and certainly prompted a rethink on geological time and possible extinctions.

Subsequent chapters take us through the many people she met, finds she made and her growing influence on the nascent science of geology and palaeontology. This included her recognising many previously unknown facets, such as coprolites and squid ink sacs, as well as specimens new to science, which she communicated to her contacts within the scientific world who then published this information, often (but not always) acknowledging her input. Throughout most of her life, she was dependent on her fossil finds for income, and was often in financial trouble. One of the highlights is the number of geologists and other members of the gentry who supported her, with moneys generated by the sale of

(continued on page 40)

Assynt and Scotland's NW Highlands: Northumbria, August 2021

Paul F. V. Williams

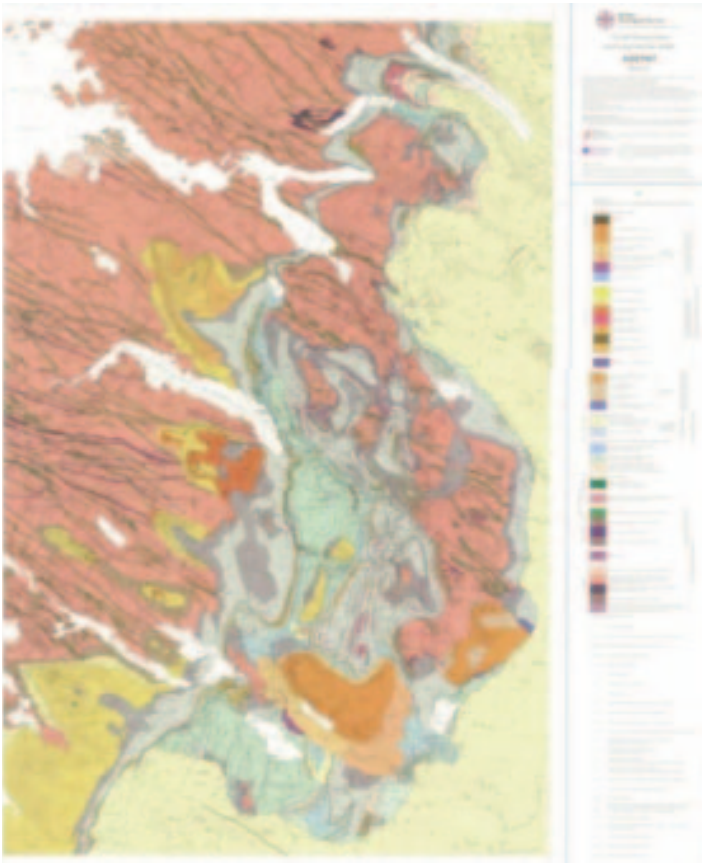
Introduction

In the summer of 2021 Northumbria OUGS organised and ran the first long OUGS event since the start of the Covid-19 pandemic. With Covid lockdown regulations easing and after much careful discussion and planning, plus the application of stringent biosecurity protocols, the trip went ahead in early August 2021. It was attended by eight gleeful OUGS members eager to get back out in the field again after lockdown. As an added bonus the party were to stay in the same hotel as the legendary survey geologists Ben Peach and John Horne had stayed in during their monumental work in the NW Highlands!

Regional significance

The NW Highlands of Scotland, especially the Assynt district, hold a global significance for major developments in the science of geology. Just as at Siccar Point, where James Hutton was able to formulate his ideas about the immensity of geological time, so too the NW Highlands provided a major breakthrough in the understanding of mountain-building processes. It was here in mid- to late-1800s that the great and good of geology at the time observed, recorded, synthesised and hypothesised about how mountains were made. And it was here that a great geological controversy that had engaged the foremost thinkers in the science for many years was finally resolved.

Figure 1 BGS Map of the Assynt area showing the geological complexity of the region. The numerous dark lines transecting NNW–SSE across the Lewisian Gneiss Complex, coloured pink, are Scourie dykes (© NERC).



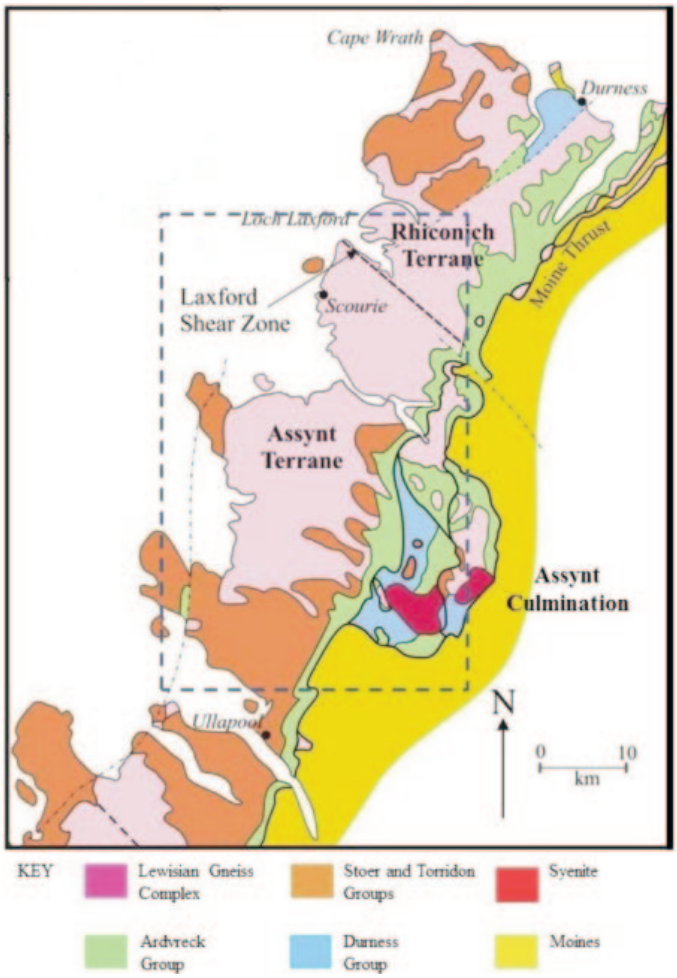


Figure 2 Map of the NW Highlands showing generalised geology. Dashed box indicates area covered on the trip (modified from BGS and NW Highlands Geopark sources).

The 'Highland Controversy' (Oldroyd 1990), as it was known, centred on the appearance of schists and gneisses above dolomitic limestones or quartzites in many sections in the NW Highlands. The view of Murchison, and later of Geikie (the Geological Survey view), was that they simply represented a continuation of a normal stratigraphic succession. However, others such as Nichol (1857) and Lapworth (1884) held the opposing view: that the metamorphic rocks appearing above unmetamorphosed sediments meant the metamorphic rocks had to have *somehow* been brought in from elsewhere subsequent to their metamorphism. The 'somehow' was the significant word, for at that time in the mid-1800s there was no recognised mechanism by which this whole-scale movement of crust could be facilitated.

Geological framework

The geology of the region is summarised and detailed in the accompanying maps (Figs 1 and 2). The geological foundations of the Assynt district are composed of a basement of Archaean to Early Proterozoic gneisses, the 'Lewisian Gneiss Complex'. This is named from its type-area in the Western Isles, and much of our understanding of these ancient rocks is the result of the pioneering work of John Sutton and Janet Watson (1951).

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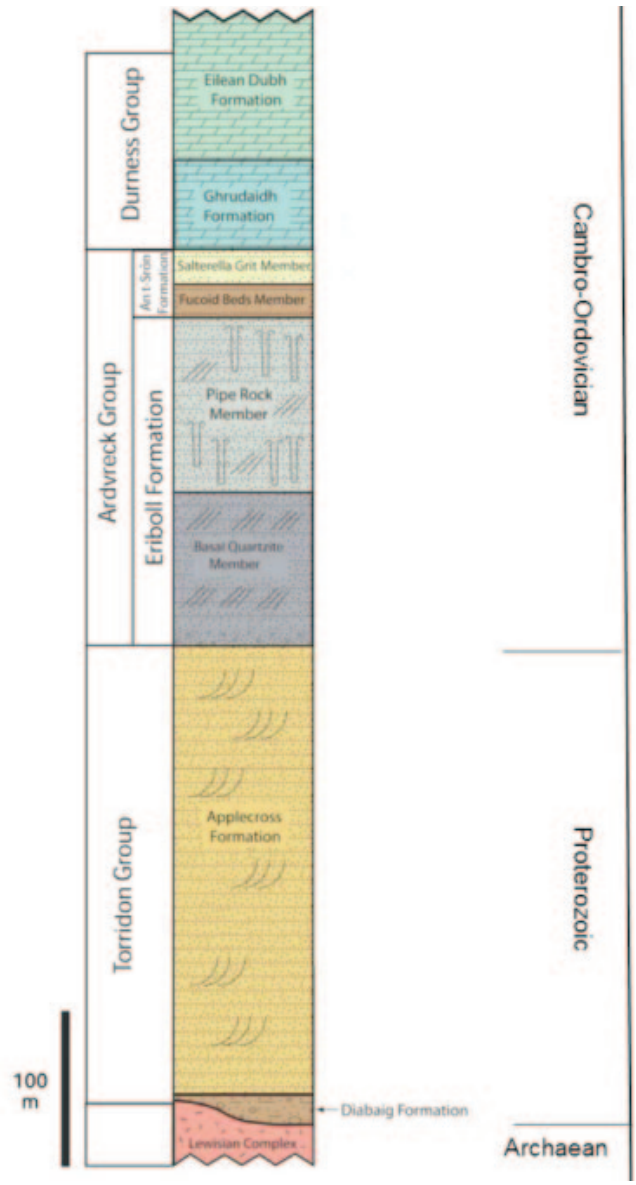

Figure 3 Stratigraphic Column showing the succession of rock units found across the Assynt District and NW Highlands (modified from Goodenough and Krabbendam 2011; reproduced with kind permission of the Publishers, Edinburgh Geological Society).

Most of this gneiss has igneous origins and has been variably metamorphosed to high grade during several tectonothermal episodes. This is overlain with significant unconformity by a thick series of red continental clastics of Proterozoic age, known generally as the 'Torridonian' sandstone. These can be subdivided into an older Stoer Group, dated at *c.* 1200 Ma, and a younger Torridon Group, with an age of *c.* 1000 Ma.

These are in turn overlain unconformably by shelf siliciclastics and carbonate platform sediments of Cambro-Ordovician age. This succession begins with gleaming white quartzites, so characteristic of the NW Highlands, passing up into sandy sediments, and capped by a variable thickness of dolomitic carbonates known generally as the 'Durness Limestone'. These units are summarised in the accompanying stratigraphic column (Fig. 3). The Durness Limestone succession is terminated abruptly above by several major sub-horizontal planes of tectonic disturbance, with low-grade schistose rocks or even gneisses above these dislocations, to complete the observed succession.

Finally, intruded into the area is a suite of intriguing highly alkaline silica-undersaturated syenite plutons of Late Silurian Wenlock age.

Geological history of the area: a synopsis

The geological history is long and complex given the incredible age-range of the rocks present in the area. Only a brief and simplified overview is presented here, covering the major events giving a background context to the week. For more detail the reader is directed to the field guide to the area by Kathryn Goodenough and Marten Krabbendam (Goodenough and Krabbendam 2011, reprinted 2018)

Within the ancient Archaean cratonic area that now underlies the northern hemisphere, different areas experienced different detailed histories at differing times. For the area that now underlies the North Atlantic region, including Britain, several major periods of compressional continental collision have been identified, together with episodes of extension. It is important to recognise that for the earliest events they would have probably taken place close to the earliest development of plate tectonics on the planet, involving the earliest continental crust after it separated.

The compressional events record periods of intense ductile deformation at deep crustal levels along with brittle deformation at higher levels, and high-grade metamorphism. Extensional events are recognised by the presence of mafic intrusives — dykes generally — and are thought to represent periods of ocean-opening. Reworking of earlier terranes is commonplace. The detaiedl unravelling of these complex tectonothermal histories has only been made possible by advances in mass spectrometric analysis during the last few tens of years. These Archaean to Early Proterozoic events are summarised in Figure 4.

There is a significant time-gap in the record before the deposition of the thick succession of continental clastics, representing a major period of erosion of the Archaean-Proterozoic basement.

Figure 4 Timeline of Archaean/Proterozoic Events for the NW Highlands.

ARCHAEAN TO PROTEROZOIC EVENTS

HEBRIDEAN CRATON: PROTOLITH AGES
Assynt Terrane Tonalite: 3030 Ma; Rhiconich Terrane Granodiorite: 2840 – 2680 Ma;

BADCALLIAN EVENT: (Assynt Terrane) 2490 Ma; collisional orogenesis, granulite facies metamorphism, ductile deformation; later intrusion of granitic sheets; also mafic pods, now amphibolitised;

INVERIAN EVENT: between 2490 Ma and 2400 Ma; continental collision, crustal re-working, ductile deformation; amphibolite facies metamorphism; localised intense shearing;

SCOURIAN EVENT: 2400 Ma – 2200 Ma; continental rifting, lithospheric extension, oceanic crust formation, mafic dyke intrusion and metamorphism; second phase of mafic dyke intrusion, extension, and new oceanic crust formation 2000 Ma;

LAXFORDIAN EVENT: (Rhiconich Terrane, also recognised over Assynt Terrane); preceded by granitic sheet intrusion, 1855 Ma., subduction zone melting 1740 Ma, ocean closure, subduction melting, continental collision; ductile deformation, amphibolite grade metamorphism; injection of granite sheets; second phase 1675 Ma., crustal re-working, metamorphism, migmatisation, injection of granite sheets;

PROTEROZOIC WEATHERING: Stoer Group erosional redbeds 1200 Ma., alluvial fan conglomerates, carbonates, braidplain sandstones; post orogenic marginal basins;

GRENVILLE OROGENY: (not broadly recognised in Britain) 1100 Ma., - 980 Ma.; assembly of Rodinia supercontinent; orogenic foreland basin sourcing Torridon Group clastics 1000 Ma;

These sediments were deposited in post-orogenic basins, and for the wider and larger-scale depositional basin within which the Torridon Group was deposited, a setting marginal to the Grenville Orogen is suggested; and it is believed that it represents the orogenic foreland basin to the Grenville Orogen itself (Krabbendam *et al*. 2008).

This Grenvillian event is not recognised in Britain other than possibly in some metamorphic rocks of limited extent on the Scottish west coast. The Grenvillian compressional event was in part responsible for continental accretion during the formation of the supercontinents, firstly of Rodinia and latterly of Panottia in the Neoproterozoic. The break-up of the postulated Panottia supercontinent gave rise to separate continental blocks of Laurentia, Baltica and Siberia, separated by the expanding, global Iapetus Ocean. It was on the Laurentian marginal continental fringes and shelf of this ocean that the siliciclastic/carbonate succession of the Cambro-Ordovician was deposited.

By mid Ordovician times, *c*. 490 Ma, ocean closing had begun as global plate dynamics changed and heralded in the onset of the Caledonian Orogeny. For the rocks of the Assynt District the Scandian compressional phase at *c*. 450 Ma is significant. During this event large-scale thrusting to the NNW resulted in translocation of major sections of crust over great distances in the order of hundreds of kilometres along low-angle thrust planes. And it was the observation of these planes of dislocation in the Assynt landscape that led the early workers to formulate ideas on how mountains were made, and the final resolution of the Highlands Controversy.

Finally post-orogenic collapse and thermal relaxation initiated felsic magmatism across the whole Caledonian Orogen and intrusion of plutonic bodies. This post-Caledonian intrusive suite is primarily granitic, although more intermediate compositions are recognised on a minor scale.

The excursion, day by day

Day 1

For the first few days of the week we concentrated on studying the Archaean/Early Proterozoic basement rocks. The examination of *c*. three-billion-year-old Lewisian gneisses began at the type-locality of Badcall Bay with some grey banded pyroxene granulites exposed in a road cutting (Fig. 5). These had a protolith age of *c*. 3.03 Ga for the tonalitic parents, which had experienced granulite facies metamorphism during the Badcallian event, dated *c*. 2490 Ma. These gneisses have previously been identified as different from those exposed farther north, and are regarded as a separate terrane unit, the Assynt Terrane.

Figure 5 Assynt Terrane Lewisian Gneiss, Badcall Bay. Tonalite-hosted grey pyroxene granulites of the Badcallian Palaeoproterozoic-age continental collision event, c. *2490 Ma.*

Figure 6 Scourie amphibolite dyke invading Badcallian gneiss, Badcall Bay.

At the south-eastern end of the road cutting the party identified a cross-cutting linear feature intruding the granulites (Fig. 6). From the amphibole-dominated mineralogy this intrusive unit had experienced a lower grade of metamorphism than the gneisses had, pointing to a subsequent, later, event. This amphibolite had originally been a mafic dyke, and had intruded the Badcallian gneisses during the extensional Scourian event at *c.* 2200 Ma.

Travelling north to the vicinity of Loch Laxford, road cuttings in the area again show banded gneisses, but these are quite different from those at Badcall Bay (Fig. 7). These gneisses are quartzo-feldspathic and abundant amphibole instead of pyroxene. The metamorphic grade of these present gneisses is lower than the Badcall Bay examples, and ages of *c.* 1740 Ma have been determined for these rocks. The parent granodiorites were raised to amphibolite grade during the Laxfordian event, a phase

Figure 7 Road cut near Laxford Bridge: Rhiconich Terrane gneiss, pale grey, invaded by Laxfordian granite sheets, pink. Dark units are dismembered Scourie dykes, now amphibolitised by the 1740 Ma Laxfordian collisional event.

Figure 8 Near Laxford Bridge (width of section 2 m): Scourie dyke, black, showing shearing, folding and amphibolitisation during the Laxfordian event invaded by thin, early Laxfordian felsic sheets which also show later Laxfordian folding, and all cut by wide, pink late Laxfordian granite sheets.

of continental collision beginning with injection of granitic sheets at *c.* 1855 Ma — a major compressional phase at *c.* 1740 Ma, culminating with a final phase of felsic injection at 1640 Ma. With protolith ages of *c.* 2840 Ma and lower-grade metamorphic facies than the Badcallian gneisses, these are regarded as a separate terrane unit, the 'Rhiconich Terrane'

Sections in the road cuttings studied around Loch Laxford also show black, discontinuous foliated and folded units within the grey gneiss (Fig. 8). These are rich in amphibole and are identified as mafic Scourie dykes intruded prior to the Laxfordian event, and then subsequently incorporated into the Laxfordian crust during the *c.* 1740 Ma event.

South of Loch Laxford zones of intense shearing can be identified in some road cuttings, which mark the tectonic junction between the two terrane units. Much of the gneiss in this area has become unrecognisable, and is represented instead by mylonites (Fig. 9).

Figure 9 The Laxford Shear Zone south of Laxford Bridge. Steeply dipping Rhiconich Terrane gneisses cut by numerous Inverian-age shears with attendant mylonitisation and subsequent deformation and amphibolite facies metamorphism in the Laxfordian event.

Figure 10 The Laxford Shear Zone from near Bradnaby showing shears in the landscape. The depressions represent weathered-out regions of intense shearing.

This is the 'Laxford Shear Zone' (LSZ), a major tectonic boundary zone along which the two separate terrane units have become juxtaposed at some point before the Laxfordian event. This terrane boundary is easily recognised in the landscape as a series of upstanding ridges separated by gullies as the zones of intense shearing weather out (Fig. 10).

The area around Port Tarbet is situated just a little south of the LSZ, in Assynt Terrane gneisses showing the characteristic grey-banded appearance, and rich in pyroxene. Rocky knolls in the area also showed some brown micaceous schists, quite different from the surrounding grey gneiss (Fig. 11). These schists are quite fascinating, as they are believed to be derived from supracrustal sedimentary components. Reliable dating has as yet been impossible on these units, but they are contiguous with the gneisses, so must have a shared history; and they are thought to represent remnants of an ancient sedimentary cover.

Major exposures of characteristically grey and banded Badcallian gneisses around Port Tarbet are also cut by later granitic sheets (Fig. 12, *opposite*). These felsic intrusions have been dated at post-2490 Ma, and are related to a post-Badcallian collisional event, the Inverian. Metamafic pods are also related to

Figure 11 Brown Schists exposed in rocky knolls, Port Tarbet

Figure 12 Port Tarbet area: grey Badcallian-age pyroxene granulites of the Assynt Terrane cut by numerous Late-Badcallian/Inverian-age pink felsic sheets.

this Inverian event, along with episodes of shearing and folding. In common with the Rhichonich Terrane gneisses the Assynt Terrane gneisses are also intruded by Scourie dykes. This suggests that by Scourie event time, *c.* 2200 Ma, both terrane units had become juxtaposed. However, the Scourie dykes in the Assynt Terrane have been much less affected by the later Laxfordian event, and in places are relatively undeformed. Similarly, the gneisses here have also suffered little in the way of retrograde metamorphism by the subsequent Laxfordian event, the pyroxene granulites being more resistant to subsequent metamorphic changes.

In one part of this section Inverian-age folding can be seen to disrupt the Badcallian gneissosity with a Scourie dyke cutting the Inverian deformation. The dyke itself has been weakly sheared by later Laxfordian deformation. In this one section alone, 750 million years of Earth history is presented, with the equivalent of three orogenies and one ocean opening event, *all on one rock-face* (Fig. 13)!

Figure 13 Inland from Port Tarbet (section height 3 m): Pale grey Badcallian pyroxene granulites of the Assynt Terrane with dark to black metamafic units folded by the Inverian event, folding also affecting granulites but not easy to discern in this image. Intruded black mafic Scourie dykes dismembered and sheared by Laxfordian deformation. This rock face shows effects of three collisional orogenies and one extensional rifting/ocean opening crustal accretion event.

Figure 14 Sunset over Loch Assynt from the hotel dining room.

Our visit to this last location formed a fitting close for the day, and the party made the short journey back to the hotel, wondering just how much longer it would have taken Peach and Horne to get back to the hotel on horseback. That evening the party was treated to the spectacle of an Inchnadamph sunset from the dining room windows to complete a magic day (Fig. 14).

Day 2

Next morning the party travelled north again, to Scourie, the type-locality of the Scourian extensional event. On the seashore a 20 m-wide slot had been weathered out, and remnants of the rock remaining were rich in amphibole and plagioclase (Fig. 15). The edges of this body were in contact with grey gneisses and an orientation could be ascertained for this obvious linear feature. A slot in the landscape high up on the far skyline was aligned with the outcrop] on the beach, and was the likely continuation of the feature across the landscape. This had originally been a mafic dyke, now metamorphosed, and was intruded into the Assynt Terrane Lewisian gneisses during the Scourian extensional event at *c.* 2200 Ma.

Figure 15 Scourie Bay: part of 20 m-wide mafic Scourie Dyke cutting pale grey Assynt Terrane granulites,

Figure 16 Achmelvich Bay: Assynt Terrane Badcallian-age pyroxene granulites with shallow-dipping gneissosity, and dark, folded Inverian-age metamafic pod.

Travelling south to the area around Achmelvich the beach was backed by more exposures of gneiss among which numerous holidaymakers reclined, enjoying the warm August sunshine. Here grey gneisses were invaded by many pink felsic horizons, together with some mafic elongated oval patches some tens of centimetres in size. In the centres of some of the black 'augen' structures olivine grains can be seen. At this locality the gneissic banding dipped at only a shallow angle (Fig.16). Traversing north along the track to the next bay, another mafic Scourie dyke was encountered, which appeared relatively unaffected by later tectonic activity other than the development of shear zones only a few centimetres in width at the very edges of the contact of the body with the surrounding gneisses (Fig. 17).

At the second bay it was immediately apparent that the gneissic banding was much more steeply dipping, and there were numerous 100–200 mm-thick pink felsic bands in the grey gneiss too (Fig. 18). The increasing dip of the gneisses, plus the appearance of more felsic intruded material, was the result of the Inverian event, another phase of crustal compression that followed the main Badcallian compression witnessed across the Assynt Terrane. As well as intrusive felsic sheets, metamafic pods are also found (Fig. 19), and the Inverian is characterised as a whole by zones of major shearing — this location being within one such shear zone.

Figure 18 Achmelvich Bay: Badcallian-age pyroxene granulites showing steeply dipping gneissosity and intruded by Late Badcallian/ Inverian age felsic sheets.

The metamafic pods situated at the centres of sheath-folds proved fascinating. Within the mafic cores of many of them there are grains of olivine, and overall geochemical studies suggest that these metamafic units could have been derived from ancient oceanic crust. That observation, coupled with the occurrences of potentially supracrustal sediments in the area, could indicate that these were ophiolitic crustal remnants incorporated into the Badcallian continental crust as part of the Inverian crustal collision event. Indeed, some of the mafic pod mineralogy and geochemistry suggests affinities with suprasubduction zone ophiolitic crust. We could thus be looking at Britain's oldest ophiolite!

The party walked north observing that the gneisses become much more sheared and much less gneiss-like through the rocky traverse. We finally reached a point where the clifftop is incised by a major cleft. The gneisses hereabouts are no longer recognisable as gneisses, but have been transformed into flinty mylonites (Fig. 20, *oppopsite*). At this location we were within one of the zones of intense Inverian shearing within the Canisp Shear Zone,

Figure 17 Scourie mafic dyke (left) cutting Assynt Terrane pyroxene granulites (right) at Achmelvich. Dyke shows minor shearing at margins as a result of the Laxfordian event. Hammer head resting on marginal shears in the dyke.

Figure 19 Inverian-age amphibolite grade metamafic pod with Inverian-age sheath folds in Badcallian granulites of the Assynt Terrane, Achmelvich Bay. The metamafic pods have affinities with oceanic crust; they could represent Britain's oldest ophiolite.

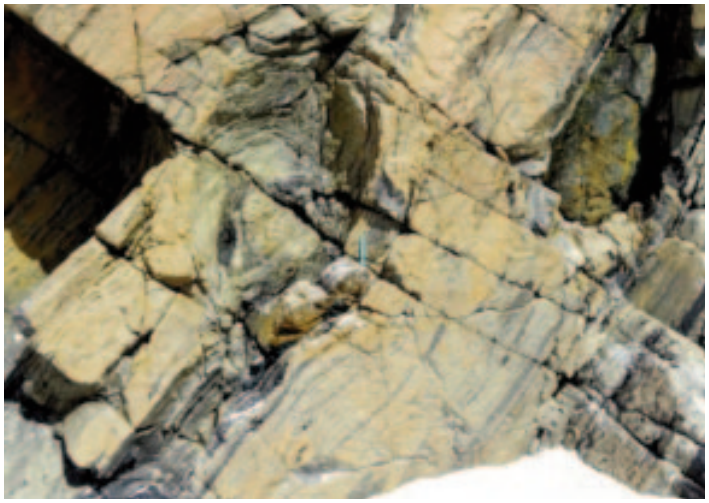

Figure 20 The Canisp Shear Zone at Achmelvich, in a zone of intense shearing and mylonitisation. Shearing initiated as part of the Inverian event, with reactivation during the Laxfordian.

a major structure that we had been traversing during the day, and one that had been re-activated during the Laxfordian event. After marvelling at the shear structures displayed in the cliffs (Fig. 21) the party returned to the cars and returned to the hotel after another incredible day.

Day 3

By the third day we were getting use to *c.* three-billion-year-old gneisses, and on the beach at Clachtol the party could now easily recognise them. But there is something quite different at this location as well! Yes, there are gneisses in places, but also some red, layered rocks that on examination can be seen to display a fragmental texture! These are *sediments* — not something the party had come across on this trip so far. With the abundance of reddened quartz grains we could identify this sediment as a sandstone. It seemed to lie on top of the gneisses, so following a clifftop path we came to a point where we could look down onto the lower surfaces of these red sediments and were able to examine the actual junction between the gneiss and the sediment (Fig. 22).

In places the gneisses seem to penetrate the sediment, and in other places seem to lie within hollows on a very undulating gneiss surface. At other places the contact is marked by poorly

Figure 21 Some of the group at the CSZ zone of intense shearing, Achmelvich.

Figure 22 The Archaean/Proterozoic unconformity at Clachtol; hammer head is resting on top surface of Lewisian gneiss which is overlain by basal Stoer Group Mesoproterozoic sediments.

sorted gneiss cobbles in a red sandy matrix. This is a significant angular unconformity, and with the major undulations across the gneiss surface it has been identified as a buried-landscape. The sandstones and conglomerates are the basal deposits of the Proterozoic Stoer Group, deposited within a fluvial braidplain environment in a continental setting. This setting was arid at times, as witnessed by the numerous desiccation structures identified further along the beach (Fig. 23).

A few kilometres north along the coast more Stoer Group sediments are exposed, displaying many examples of cross-stratification and rapid wet-sediment deposition under high-flow regimes, along with fining-up flood deposits.

Taking the clifftop path the party made its way to the prominent feature of Stac Fada. Here very hard, dark red/brown rocks contain fragments, mainly rounded, of gneiss and red sandstone, along with smaller fragments of what look like volcanic glass in a fine matrix (Fig. 24, *overleaf*). This intriguing unit has been identified as an impactite — the ejecta blanket from a major bolide impact in the northern hemisphere in the Proterozoic (Amor *et al.* 2008; Parnell *et al.* 2011; Reddy *et al.* 2015). The exact point of impact is yet to be identified, but one possible candidate is in the sea of the Minch, which in Proterozoic times

Figure 23 Stoer Group Mesoproterozoic sediments showing desiccation structures, Clachtol Bay.

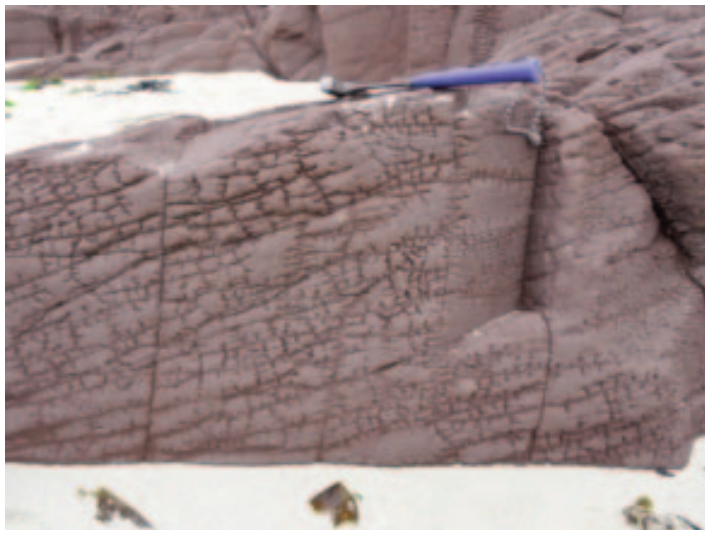

Figure 24 The Stac Fada Impactite showing rounded blocks of Lewisian gneiss embedded in finer matrix, Bay of Stoer.

would have been a continental land surface. While we were at this locality we saw further Stoer Group sediments exposed in cliffs to the north, and although not visited, some light-coloured horizons were algal limestones, the oldest fossils in Britain (Fig. 25)!

The party then travelled to the northern shore of Loch Assynt, where more red sandstones and conglomerates are exposed in roadside cuttings. These red sandstones again show fluvial cross-stratification and reddened continental characteristics, but are about 200 Ma younger than the 1200 Ma old Stoer Group seen earlier. These younger Torridon Group sediments are from a similar fluvial braidplain continental environment as the older Stoer Group. One examined section revealed a conglomeratic base to the sandstones beneath, in which some weathered crystalline rocks were found. Farther along the road some good exposures of these crystalline rocks can be identified as gneisses. This section shows a significant undulating gneiss surface identified as an ancient buried landscape, which is capped by red Torridon Group sediments, in-filling hollows and banked-up against some topographic highs. This unconformity studied by the group represents a time gap in excess of a staggering two billion years of Earth history (Fig. 26)! The party took some time marvelling at this spectacle, and what it represented.

Figure 25 Stoer Group Mesoproterozoic sediments at Bay of Stoer. White horizons under the vegetation at top of section are algal limestones, Britain's oldest fossils.

Figure 26 Unconformity between Archaean Lewisian Gneiss and Proterozoic Torridon Group clastics. The Party standing on the top surface of the gneiss, the unconformity surface representing a staggering time interval of two billion years.

The Stoer Group has a Proterozoic age of *c.* 1200 Ma, while the Torridon Group is dated *c.* 1000 Ma. These are both deposited in major continental basins, but the basinal axis of each is different, and for the Torridon Group the depositional basin is believed to be very much bigger in extent. At around this time major global continental reorganisation was taking place and supercontinent formation was underway, facilitated in part by the Grenville Orogeny. Over the Proterozoic cratonic area that eventually became northern Britain there is very little evidence of any continental collisional orogenesis other than some eclogitic rocks of this age found in the area around Glenelg (Sanders *et al.* 1984). However, detrital zircon studies of Torridon sediments (Krabbendam *et al.* 2008) suggest that they have been derived from the Grenville Orogen, and that the Torridon depositional basin was in fact the foreland basin to the Grenville Orogen itself.

After these amazing revelations it was time to bring proceedings to a close for this day, and on driving back to the hotel we noticed that the red Torridon sediments gave out farther along the road, and were replaced by gleaming white rocks that were to form the subject of the next day's studies.

Day 4

Picking up where we left off the previous day it was not apparent from the roadside where the Torridon Group sediments ended and the gleaming white rocks started, but the junction had to be somewhere in an area of no exposure. The first exposures of these white rocks showed them to be very hard, and on detailed examination an abundance of clear quartz grains indicates that they are sandstones, specifically quartz arenites due to the presence of included feldspar grains. These rocks show variations in grain size, with some quite pebbly horizons, and have well developed cross-stratification in places.

Farther along the section there is herringbone cross-stratification, indicating deposition under oscillating current directions — usually indicative of tidal effects. These strata dip gently eastwards, so walking through the roadcut in that direction brought us to younger horizons. After an area of no exposure outcrops are again visible at Skiag Bridge, where an abundance of animal burrows in the quartz arenites indicates an identifiable horizon. The burrows are Skolithus trace fossils, indicative of the

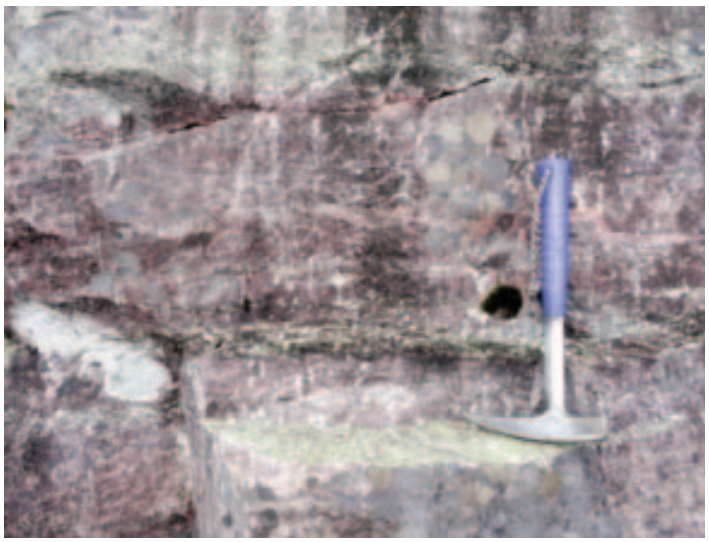

Figure 27 Pipe Rock with vertical Skolithus burrows. Pipe Rock Member, Eribol Formation, Ardvreck Group Cambrian age sediments, Skiag Bridge.

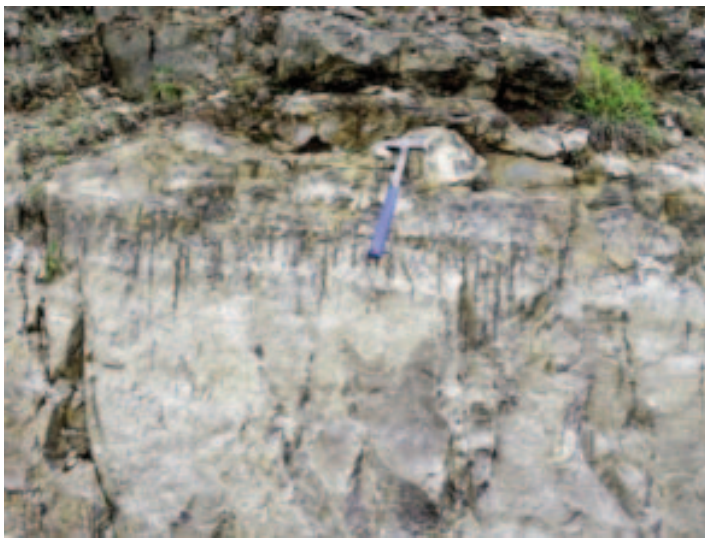

Figure 28 Burrowed and eroded top of the Salterella Grit marking the transition from a tidal/subtidal siliciclastic shelf to the arid carbonate platform sabkha environment of the Durness Group.

Cambrian age Pipe Rock Member of the Eribol Formation, part of the Ardvreck Group (Fig. 27).

Continuing our traverse eastwards to higher horizons we passed through a series of sand-dominated clastic sediments of varying grain size, representing fluctuations in water depth over a shallow coastal plain.

Fine-grained Fucoids Bed sediments with abundant trace fossils — indicating deeper water conditions — are later replaced by coarse-grained shallow-water deposits of the Salterella Grit Member higher up the succession. As we reached the top of the Salterella Grit, burrows became plentiful, with the top of the unit indicated by an erosion surface packed with burrows (Fig. 28). At this junction the clastic-dominated sediments are replaced by carbonates, specifically dolomitic carbonates of the Durness Group. Pale grey Ghrudaidh dolomites are developed above the junction, and are followed by lighter-coloured Eilean Dubh dolomites at the top of the succession exposed in this area. Taken as a whole, this shelf succession represents sedimentation on a shallow coastal plain with tidal influence transitioning to a shallow tidal/sabkha environment under increasingly hot and arid climatic conditions. These were the shelf deposits along the coastal fringes of the enlarging Iapetus Ocean.

This particular locality also provided a view of another of Assynt's 'classic' geological features. Looking south across Loch Assynt the 'double unconformity' is well displayed (Fig. 29). At loch-level, rounded hummocks in the landscape indicate the presence of Lewisian gneisses, which are truncated above by an obvious planar, sloping dislocation with layered strata appearing above. These layered strata are Torridonian sandstones lying unconformably above the Lewisian gneiss. Near the top of the hillside the sandstones are themselves truncated by another planar dislocation, the unconformity between the Cambrian quartzites and underlying Torridonian. An amazing spectacle, so clearly presented!

Earlier in the week the party had viewed a section from across the shore of Loch Glencoul (Fig, 30). Here the rounded knolls of

Figure 29 The 'classic' double unconformity in the landscape, Loch Assynt. Sub-horizontally bedded Torridon Group clastics overlying hummocky Lewisian Gneiss and truncated above by shallow-dipping Eribol Formation quartzites.

Figure 30 Loch Glencoul and the classic view of thrust-slices overriding Cambro-Ordovician sediments. In the latter part of the 19th century this view helped to explain how mountain-building processes occurred.

Figure 31 The party examining repetition of thrust slices of Fucoid Beds and Salterella Grit in the countryside above Skiag Bridge. Upstanding ridge in foreground composed of Salterella Grit. Group members standing on easily weathered Fucoid Beds.

Figure 32 The Moine Thrust exposed in the River Cannaird, Langwell. Thrust runs middle right to lower left, and dips into the image; c. 2 m of Moine rocks rest above the thrust.

countryside suggest that the gneiss is overlain by the now familiar and recognisable quartzite/carbonate succession of the Cambrian, and one can also observe an obvious major break above the dolostones. Above, as the party noticed, rounded knolls reminiscent of gneiss can be recognised.

This section has international recognition as one of world geological significance because it was here in the late 1800s that the understanding of mountain-building processes was developed. Benjamin Peach, John Horne and Geological Survey colleagues (Peach *et al.* 1907), aided by the experimental work of Henry Cadell (Cadell 1888), recognised that the major break above the Durness Group dolostones represents a low angle fault along which geological strata had been pushed over those beneath. The notion that "gneiss and schist had been somehow forced over quartzite" had been suggested earlier by James Nicol in 1857 and in 1861(Nicol 1857, 1861), and the idea of thrust faults and compressional tectonics having a major role in mountain-building had also been postulated by Charles Lapworth in 1884 (Lapworth 1884) after several visits to the NW Highlands. It was here at Loch Glencoul, however, and at a similar section at Loch Eribol to the north, that the ideas finally became crystallised into a complete theory of how mountains form — by low-angle thrust faulting under lateral forces of compression.

The thrust faulting here is the result of major orogenic activity in the Ordovician, during the closure and final demise of the Iapetus Ocean along with the attendant continental collision as the Caledonian Orogeny progressed. During the Scandian phase there was a major translocation of material in a roughly NNW direction, which manifests itself spectacularly in the landscape of the NW Highlands, and in particular in the Assynt District. Major truncation of units and repetition of strata can be seen across this whole tract of country. The party was able to examine this, traversing over rough moorland following ridges and hollows in the landscape that represent repeated thrust-slices of easily weathered Fucoid Beds and more resistant Salterella Grit horizons (Fig. 31), features that are part of the major thrust activity, albeit here on a smaller scale. For much larger-scale features such as those seen across the loch at Glencoul the party had to wait until Day 5.

Day 5

On Day 5 the party travelled south towards Ullapool, where a major thrust, the Moine Thrust — the oldest of the Scandian thrusts — is displayed in the landscape creating, a waterfall in the River Cannaird. Here schistose rocks of the Moines had been thrust over an attenuated Lower Palaeozoic succession above Lewisian Gneiss (Fig. 32).

To witness this at a much larger scale, however, the party made its way northwards again to the major geological heritage site of Knockan Crag, another of significant international repute. Here part-way up the trail massive Moine rocks have been thrust spectacularly over Cambro-Ordovician dolostones, with the blatantly obvious junction of the Moine Thrust denoted by flinty mylonitic crush-rock (Fig. 33). This exposure was eagerly 'devoured' by the delighted party, and recorded on numerous cameras and notebooks. After this excitement the party took in the view from the top of the crags (Fig. 34, *opposite*) before studying further sections in the area showing minutely sheared Moines, which show the transition from ductile to brittle deformation (Fig. 35, *opposite*). For the remainder of the afternoon the party studied more examples of thrust slices in the landscape.

Figure 33 The Moine Thrust at Knockan Crag. Sheared Moines spectacularly thrust over Cambro-Ordovician Durness Group dolostones.

Figure 34 OUGS Assynt 2021 party assembled above Knockan Crag.

Figure 36 Loch Borralan Pluton: examining syenites exposed in track-side banks, Bad na h-Achlaise forest.

Day 6

Post-orogenic felsic plutonic intrusives are commonplace across the Scottish Caledonides, giving rise to substantial bodies such as the Cairngorms and Ben Nevis. A large proportion of these are of 'granitic' composition, but other rock types are also found. Intermediate dioritic composition intrusive plutonic rocks occur in the area of the western Grampians, while alkaline plutons occur around the Iapetus Suture on both sides of the Scottish border. However, there are also some highly alkaline plutonic intrusions in the far NW Highlands.

The final day of the trip focused on this aspect of district's geological heritage.

The area around Ledmore Junction, a few km south of Inchnadamph, is underlain by the Loch Borralan Pluton, which forms the hill of Cnoc na' Stroine; the pluton extends eastwards to the Allt a' Mhuilinn, and southwards into the forest of Bad na h-Achlaise. Along the track through this forest there are outcrops of some relatively coarse-grained igneous rocks in its side banks (Fig. 36), composed of pink alkali feldspar, black melanite garnet, and what could have been mistaken for quartz had the party not been forewarned, glassy, clear to translucent, 'greasy' nepheline. This rock is thus a syenite, and the presence of nepheline indicates silica undersaturation. This rock is a nepheline syenite, Britain's only known example of a silica-undersaturated alkali syenite. Other trackside exposures, and blocks from a small disused quarry alongside them, show a similar mineralogy, which is indicative of a particular named rock type characteristic of the area — Ledmorite. This rock is now more formally known as Ledmore Nepheline Syenite.

After a boggy forest walk the party found itself close to the shore of Loch Urigil, where further excitement awaited — in some trial pits dug by NCC in the 1980s. Blocks of a grey-weathering, strange pale rock litter the pit (Fig. 37); examination of the rock reveals a crystalline texture, with interlocking white translucent to colourless clear transparent crystals, which are quite soft.

These crystals are actually *calcite*, although the rock has characteristics of an igneous rock. We were looking at a carbonatite, an igneous rock composed of primary igneous calcite. This is Britain's only known occurrence of a carbonatite! Other blocks in

Figure 35 Knockan Crag, above the Moine Thrust: intensely sheared Moines, looking at first glance like flaggy sediments.

Figure 37 Carbonatite, Bad na h-Achlaise Forest: bronze-brown flecks on broken face composed of phlogopite mica plates.

Figure 38 Excavated section, Bad na h-Achlaise forest: pegmatitic nepheline syenite with euhedral grey feldspar phenocrysts up to 100 mm in length.

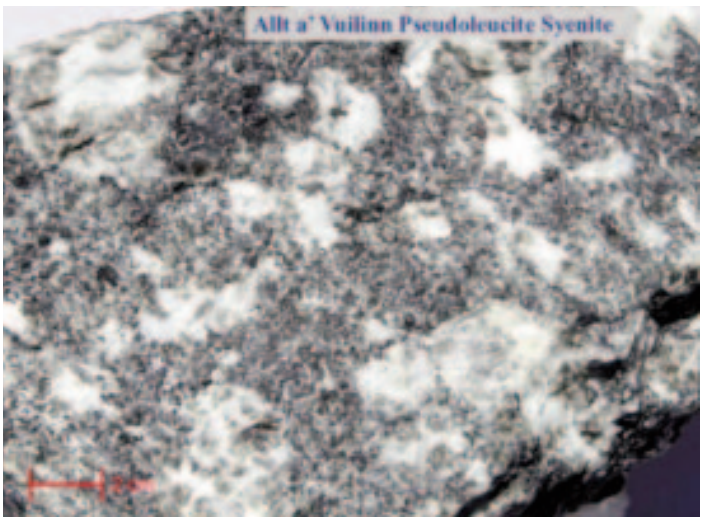

Figure 40 Borolanite(Allt a'Mhuilinn Pseudoleucite Syenite) detail, scale bar lower left. Small black melanite garnet and some biotite in groundmass. White spots after leucite composed of white opaque alkali feldspar and transparent to translucent clear colourless anhedral nepheline.

the pit show banding, with horizons of phlogopite mica within the calcite.

After examining more alkali syenites in the forest and Ledmore area, some with massive grey alkali feldspar phenocrysts (Fig. 38) the party relocated eastwards to the former Allt a'Mhuilinn quarry, the final stop of the day. Here grey crystalline rocks with numerous white spots can be found everywhere (Fig. 39). Studying the rock in detail (Fig. 40) reveals that the white spots are composed of nepheline and alkali feldspar, and an abundance of black melanite garnet. This is another of the 'classic' rocks of the area, and was originally called Borolanite.

The white spots are pseudomorphs after original leucite, another feldspathoidal mineral like nepheline. Hence again this was another silica-undersaturalted syenite, now known as Allt a'Mhuilinn pseudo-leucite syenite.

The origin of these intriguing rocks is still uncertain. The alkali content, particularly the high potassium enrichment, is usually characteristic of subducting slab influence, but this present setting is far from any of the Caledonian compressional subduction events that took place farther to the south, and earlier in time. Work continues to explain the occurrence of these amazing alkaline-undersaturated rocks.

By this time the midges had begun to make their presence very evident in the quarry, despite the party being well protected against their attacks. It was thus deemed wise to terminate the proceedings on this final day and retrace our route back to the hotel. All the party agreed this had been an exciting and enjoyable trip, and that it had been a delight to get back out in the field again amid such spectacular rocks of great historical significance for the science of geology, and amid some truly amazing scenery and dramatic landscapes. The party then made its by now customary way back to the hotel bar for refreshments before dinner (Fig. 41).

Figure 39 Borolanite in Loch Borralan Quarry (Allt a'Mhuilinn Quarry). Prominent white spots are pseudomorphs after leucite, now composed of nepheline and alkali feldspar.

Figure 41 The party enjoying refreshments in the Inchnadamph hotel bar after a day in the field.

Acknowledgements

I would like to put on record my sincere thanks to Richard and Jaimie at the Inchnadamph Hotel for looking after us all so well during the week. Their unstinting tolerance and high-quality,

efficient service is much appreciated. Putting up with rock-filled bedrooms, the 'bar rush' on returning from the field, and catering for so many varied palates cannot be easy, but they managed it always with a smile and humour, and made the party feel very much at home during our visit.

References

Amor, K., Hesselbro, S. P., Porcelli, D., Thackray, S., and Parnell, J. 2008 'A Precambrian proximal ejecta blanket from Scotland'. *Geology* **36**, 303–6

Cadell, H. M. 1888 'Experimental researches in Mountain-building'. *Trans Roy Soc Edinburgh* **35**, 337–57

Goodenough, K. M., and Krabbendam, M. (eds) 2011 *A Geological Excursion Guide to the North-west Highlands of Scotland*. Edinburgh: Edinburgh Geological Society in association with NMS Enterprises Limited

Krabbendam, M., Prave, A. P., and Cheer, D. 2008 'A fluvial origin for the Neproterozoic Morar Group, NW Scotland: implications for Torridon- Morar Group correlation and the Grenville Orogen Foreland Basin'. J *Geol Soc* **165**, 379–93

Lapworth, C. 1883–1884 'On the structure and metamorphism of the rocks of the Durness-Eriboll district'. *Proc Geol Assoc* **8**, 438–42

Nicol, J. 1857 'On the red sandstone and conglomerate, and the superposed quartz-rocks, limestones and gneiss of the north-west coast of Scotland'. *Quart J Geol Soc* 13**,** 17–39

Nicol, J. 1861 'On the structure of the North-Western Highlands, and the relationship of the gneiss, red sand-stone, and quartzite of Sutherland and Ross-shire'. *Quart J Geol Soc* **17**, 85–113

Oldroyd, D. R. 1990 *The Highlands Controversy: Constructing Geological Knowledge through Fieldwork in Nineteenth Century Britain*.U Chicago P

Parnell, J., Mark, D., Fallick, A. E., Boyce, A., and Thackrey, S. 2011 'The age of the Mesoproterozoic Stoer Group sedimentary and impact deposits, NW Scotland'. *J Geol Soc* **168**, 349–58

Peach, B. N., Horne, J., Gunn, W., Clough, C. T., Hinxman, L. W., and Teall, J. J. H. 1907 *The Geological Structure of the North West Highlands of Scotland.* Mem Geol Surv GB

Reddy, S. M., Johnson, T. E., Fisher, S., Rickard, W. D. A., and Taylor, R. J. M. 2015 'Precambrian reidite discovered in shocked zircon from Stac Fada impactite, Scotland'. *Geology* **43**, 899–902

Sanders, I. S., Van Calsteren, P. W. C., and Hawkesworth, C. J. 1984 'A Grenville Sm-Nd age for the Glenelg eclogite in north-west Scotland'. *Nature* **312**, 439–40

Sutton, J., and Watson, J. 1951 'The pre-Torridonian metamorphic history of the Loch Torridon and Scourie areas in the North West Highlands and its bearing on the chronological classification of the Lewisian'. *Quart J Geol Soc* **106**, 241–307

(continued from page 26)
their personal collections, the famous lithograph Duria Antiquior, and even an annual pension of £25 granted following the solicitations of members of the Geological Society of London to the then Prime Minister, Lord Melbourne. Quite clearly Anning was held in high regard despite her humble beginnings.

She died in 1847, and breaking with tradition, the then president of the Geological Society announced her demise to the Society at their Annual General Meeting, even though she was not a Fellow (being only a woman!).

The final two chapters of the book review her legacy and the whereabouts of many of her specimens in museums throughout the UK and the wider world. These are followed by a 'Who's Who' of the many characters who appear in the story, and by Notes, Sources and Further Reading arranged by chapter. The book ends with a useful Index and there are two collections of photographs printed on glossy paper.

This is a marvellous and masterly biography of a fascinating woman, described by a visiting Prussian naturalist as a 'Princess of palaeontology'. Apart from covering the mere facts of her life, a sense of the person is also recorded: her generosity to her friends and neighbours, her increasing scientific knowledge and input despite her limited formal education, a possible broken heart (with the finger of suspicion pointed at Henry De la Beche of all people, and contrary to the suppositions of the recent film *Ammonite*), and the growing sense of her own worth highlighted perhaps by a rather feisty exchange with the editor of the *Literary Journal*.

I spotted two marginal errors: an extra definite article appears on p68 and an 'of' disappears on p138. One tiny criticism is that the print size appeared rather small to my eyes — perhaps I should now wear my reading glasses! This book is one of the most enjoyable I have read and is highly recommended.

— Charles Hugkulstone, OUGS South East Branch Soft Rock Editor

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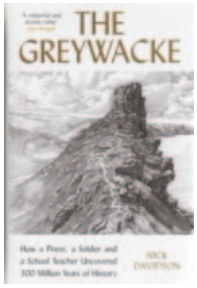
Book review

Davidson, Nick 2021 *The Greywacke: How a Priest, a Soldier and a School Teacher Uncovered 300 Million Years of History.* London: Profile Books (ISBN 978-178816-377-4; 234pp, plus Glossary and Notes; hardback £20, paperback £10.99)



My short review is that *The Greywacke* is well-written, engaging and easy to read. I recommend it.

The priest, the soldier and the school teacher in the book's subtitle refers to Adam Sedgwick, Roderick Murchison and Charles Lapworth. Other geologists of the time make appearances where relevant, so the book does not exclude wider input to focus only on those three, which makes a well-rounded tale.

For those who want to know a bit more, the book covers a period of about 50 years in the 19th century, when geologists were investigating the jumble of greyish, earthy rocks in Wales and elsewhere, which up until then had been skipped over or ignored because they were not understood. In the 1820s–1830s the stratigraphic classification of Britain's rocks contained four basic categories:

- Primary — rocks born of 'fiery baptism' with crystals visible to the naked eye; the oldest foundations on which the country was built
- Greywacke — a jumbled transition phase once described as 'obscure heaps of sediment' by Murchison
- Secondary — neat bands laid down in ancient seas
- Tertiary — loose sands and gravels, the youngest and not yet 'true' rock

Unravelling the mystery of the Greywacke was a challenge of knowledge and of prestige, with some sacrificing one for the other.

The first couple of chapters introduce 'The Erratic Professor Sedgwick' and 'The Ambitious Mr Murchinson' to give a grounding of their history and experience. The book follows chronologically the story from Sedgwick and Murchison's first field trips in 1832 to Wales to 'solve' the problem through the fieldwork, proofs and controversy leading to the reclassification of the Greywacke into Silurian, Ordovician and Cambrian. Murchison is an example of why you should follow the evidence to draw a conclusion and not cherry-pick the evidence to fit your own wishes. I am surprised Sedgwick achieved anything considering his field notes contain his recipe for keeping the cold weather at bay "a cocktail of opium, cardamom, peppermint and ginger." It did not seem to work, and he later reported suffering from "severe attacks [of flu] brought on by fatigue and bad weather."

Charles Lapworth, known as Chas, comes into the story in 1864 when he moved to Scotland from Oxfordshire to teach English and Art in Galashiels. Chas was a fan of Walter Scott's novels and keen to explore the area. I found the way the author described how Lapworth collected, organised and interpreted his findings to be particularly clear in explaining how attention to detail and handling the data you are gathering leads to discovery without getting lost in the technical explanations.

This is not a scientific textbook, but it helps place scientific discoveries and methods in context.

— Helen Coombs, BSc Hons (Geosciences), OUGS Information Officer

Living in a post-glacial landscape: "Lumps, bumps, hollows, and wandering rocks" — Bas Chablais, Haute Savoie, France

Linda Fowler

Is there anything to see here?

In 2018 I moved from Hereford to the Bas Chablais area of Haute Savoie department in south-east France, exchanging a notable Silurian inlier and the Old Red Sandstone of the Welsh Borders for the much younger Alpine molasse basin south of Lake Geneva and north of the French Alps. (Fig. 1)

I love getting to know the geology of a new area, and I have had plenty of practice during a peripatetic life, but initially Bas Chablais did not look particularly promising — flat or gently rolling farmland and woodland, singularly lacking in exposures, with steep-sided marshy hollows, streams and low ridges, although the ridge of the Voirons hills lies to the south (Fig. 2) and isolated hills, the Mont de Boisy (Fig. 3) and the Allinges Hill, lie in the region's centre. Info Terre (the French version of the BGS 'Geology of Britain Viewer') reveals that we are living on wall-to-wall "*moraine argileuse avec bloques*", or boulder clay. However, this 'clay' is richer in a sandy fraction than might be expected, and very free draining, evidenced by the ease of emptying out the above ground swimming pool at the end of each summer: no puddles!

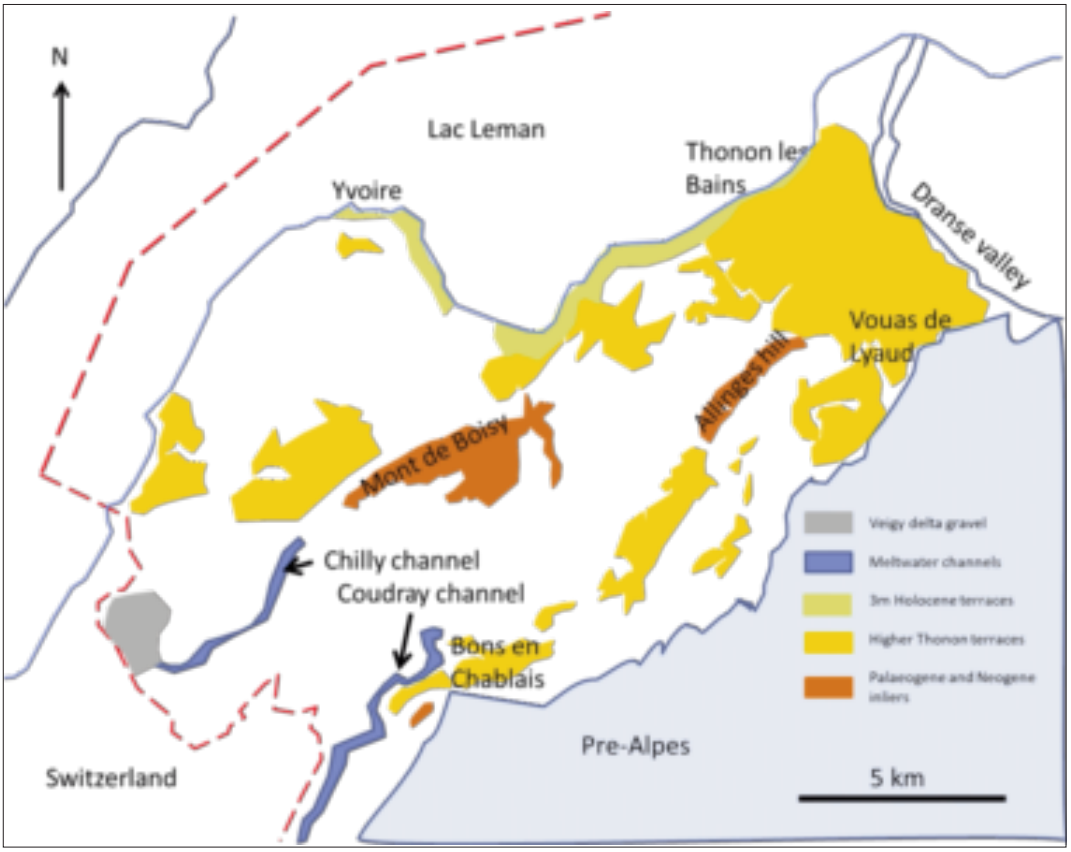


Figure 1 Geological sketch map of Bas-Chablais west of the Dranse valley, showing inliers, Würm terrace gravels, meltwater channels and meltwater deltaic deposits (based on BRGM, 2021; accessed 06-12-2021).

I am not setting out to supply an exhaustive list of glacial features in the area, these have been catalogued in detail particularly by Robert Vial (Vial 1975), more recently by Sylvain Couterrand and Amandine Perret (Coutterand 2010), (Perret 2014), and also by the Chablais Geopark in numerous leaflets and displays. Rather this is an explanation of my own journey through a landscape that was new to me.

Figure 2 The Voirons hills to the south rise 800 m above us, reaching a height of 1480 m, and the Oligocene inlier at Langin on the right was also above ice level at 770 m. The almost flat farmland in the foreground, at c. *530 m, is all underlain by boulder clay.*

Overview of local geology

My immediate local area, the western part of Bas Chablais, lies north-west of the nappes of the Chablais Pre-Alpes. The bedrock of the Pre-Alps was created by sedimentation in the expanding Tethys Ocean throughout the Mesozoic Era: as Pangaea broke up during the Triassic Period, initially dolomite and gypsum were deposited in shallow water. During the Jurassic Period rifting allowed a mid-ocean-ridge to form in the widening Tethys Ocean: massive limestones were deposited in clear, warm water.

Figure 3 The Mont de Boisy (739 m) lies between the main Rhône Glacier to the north and a tongue of ice to the south where Jan Ashton-Jones is standing.

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By the Cretaceous Period the European and African plates had begun to converge, and limestone and clay were deposited in a tropical climate.

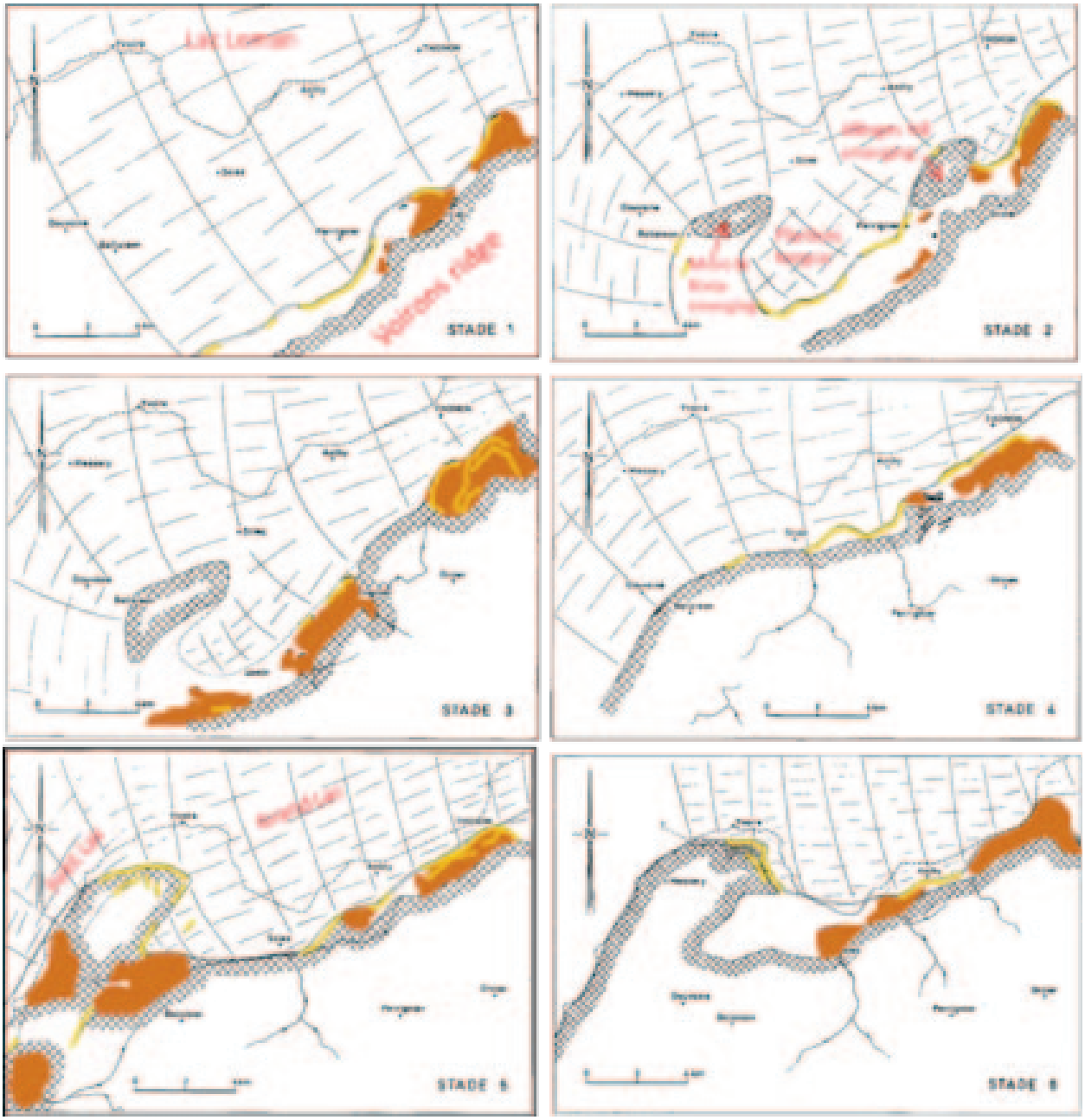
By Cenozoic times some oceanic crust (with its sedimentary layers) had been subducted under the African plate, although limestone continued to be deposited on the margin of the European plate. Continued subduction pulled the European margin under the African plate from 50 Ma to 30 Ma while marine sediments were caught in this collision — the Alpine Orogeny — and began to be stacked and deformed, forming a series of nappes. Between 30 Ma and 20 Ma ago, as the Alps rose, they were also eroded, creating thick layers of molasse sediment. Finally, in the last 2 Ma of the Quaternary Era, the area was extensively glaciated, creating today's landscape.

The bedrock of Bas Chablais is Alpine molasse of Miocene (Aquitanian 23–20.4 Ma) age , which is covered to a great extent by glacial drift deposits , except where bedrock inliers, which were above ice level at times, have been left exposed.

Glaciation

The most recent glaciation of Bas Chablais was during the Last Glacial Maximum II (LGM II), between 28 000 and 11 700 years ago in the Late Pleistocene, the Cro-Magnon era in terms of *Homo sapiens* evolution. This, and the earlier Middle Pleistocene glaciation (LGM I, Würm, 115,000–60,000 years ago) covered much of the area of the Alps and Jura mountains and at times extended as far as Lyons, 25 km to the south-west. Glaciation, because of its erosive nature, removes much evidence of its previous episodes, but retreating glaciers leave features such as

Figure 4 Rhone Glacier retreat during the Younger Dryas/Last Glacial Maximum, Stages 1–6 (terrace gravels shown in orange, moraine ridges in yellow) (adapted from Vial 1975). At the start of the Last Glacial Maximum (LGM) the entire low-lying area was ice covered (Stage 1). As the glacier retreated (Stage 2 and Stage 3) the glacier was split into a main arm north of the Mont de Boisy and a minor arm to the south. By Stage 4 the southern arm had completely retreated, advancing again a little during Stage 5 before retreating into the Lake Geneva basin by Stage 6.



erratic boulders, meltwater channels, lateral terraces or kames, frontal, and lateral moraines and kettle holes, all showing stages of regression.

A series of staged retreats left their marks here, especially noticeable as ice-marginal landforms such as lateral kame terraces and moraine ridges; there is reported to be a single drumlin (a sub-glacial landform), but I have yet to find it! The retreat at the end of the Würm is described by Vial (1975) in seven *stades* or stages (Fig. 4, *opposite*).

Stage 1: After 16 000 BP remnants of a lateral moraine ridge are the main evidence of continued occupation of the valley by a glacier. The area at the south-eastern edge of the glacier was occupied by a lake, which, as it drained, left terraces at 750 m and 640 m with lesser terraces between.
Stage 2: As the Rhône Glacier retreated, two tongues of ice remain behind the hills of Boisy and Allinges, both of which deposited ridges of moraine.
Stage 3: Further glacial retreat, and the disappearance of the Allinges tongue and regression of Boisy tongue, deposited terraces on the south-east side at Perrignier, Bons and Langin. This stage has been C^{14} dated at 14 000 years BP using a mammoth tooth.
Stage 4: Complete clearance of ice from Bons–Perrignier–Boisy zone as the Boisy tongue melted; the main glacier had retreated from Allinges hill, leaving moraine ridges; and erosion of the Brens–Machilly meltwater channel, as well as side valleys and associated terraces.
Stage 5: The Rhône Glacier was initially confined to the Petit Lac basin in the west and then retreated north-east towards the Grand Lac basin, leaving moraine ridges.
Stage 6: The glacier had retreated completely from the Petit Lac, leaving moraine ridges and terraces along the shores of the Grand Lac.
Stage 7: The glacier had completely left the Chablais area by the end of Marine Isotope Stage 2, *c.* 12 000 years BP (Perret 2014).

Visible evidence: glacial features and molasse exposures

Knowing this to be a glaciated landscape, I began by looking to see what clues to glaciation I could find in the rather featureless countryside, in the same way that the 'Fathers of Glaciology', such as Jean de Charpentier and Louis Agassiz did in the early part of the 19th century when this area gave birth to the discipline. These are the lumps and bumps (moraine and terraces), hollows (meltwater channels and kettle holes) and wandering rocks (glacial erratics) of my title.

Glacial erratics

Some of the most obvious features in the landscape are glacial erratics: the soil holds an intriguing collection of pebbles; old walls are built of a random collection of stones; small boulders are everywhere alongside roads and tracks, and larger, named examples are marked on maps. Over the centuries legends have grown up about the most prominent of these in attempts to explain their origins and they are well known local features. Used in Neolithic times for dolmens, such as the arkose blocks forming the Cave aux Fées (Fairies Cellar) dolmen in St Cergues (Sauter and Spahni 1949) (Fig. 5), and for menhirs, these blocks were regarded as a useful source of building material until the middle of the

Figure 5 The Cave aux Fees, St Cergues: a Neolithic dolmen built of slabs of coarse-grained, poorly sorted, immature arkose, plus some granite and metamorphic rock. There are six orthostats, capped by a (broken) roof slab estimated to have a mass of 15 tonnes. The dolmen is now partly buried by a landslip: (a) exterior view showing broken roof slab, (b) interior showing orthostats, c) close up of poorly sorted arkose.

Figure 6 The Pierre a Martin, Ballaison, a gneiss glacial erratic, sits on the Mont de Boisy, above Lake Geneva, with the Jura Mountains in the distance (fencing is c. *1 m high).*

Figure 7 The Pierre du Diable (or Pierre a Passet), a gneiss erratic near Allinges. 'Passet' was a pseudonym for the Devil in Savoy.

20th century, so it is likely that much data has been lost. Nowadays large erratics are popular for climbing practice.

Identification of the origins of erratic rocks can provide clues to the route and catchment area of individual glaciers. The blocks and the surfaces on which they rest can be dated using Surface Exposure Dating (SED), which measures the amount of time the rock has been exposed at the surface and by Optically Stimulated Luminescence (OSL), which measures the time since a grain was last exposed to light (Coutterand 2010; Perret 2014).

Notable examples of large erratics in Bas Chablais are the Pierre à Martin, the Pierre du Diable and the Pierre d'Amour. The Pierre à Martin (Fig 6) rests near the summit of the Mont de Boisy (*see* Fig. 3), the inlier of Miocene molasse, which forms a prominent north-east to south-west aligned hill rising 200 m above the otherwise gently undulating landscape. The erratic is a large (100 m^3) block of biotite-orthoclase-quartz gneiss, obviously unrelated to the bedrock and probably derived from the crystalline basement of Middle Penninic nappes in the Nendaz area of the Swiss canton of Valais to the east. The block has been dated at 24 343 ± 1639, which helps to constrain the date for the end of the Last Local Glacial Maximum (LLGM), named the Geneva Stadial. During this stadial the hill would have been covered with thick ice, so the erratic must have been left behind during glacial retreat as it ended (Perret 2014).

A legend tells how the Devil challenged St Martin to a rock throwing contest from the top of the Voirons hills: St Martin lobbed his rock many kilometres down into Lake Geneva ,which upset the Devil, who knew he could not beat that throw. So, in a fit of pique, he aimed his stone at the village of Ballaison, but St Martin jogged his elbow, spoiling his aim, and the rock landed harmlessly in a nearby field.

The Pierre du Diable (Fig. 7) is 8 m high, and 25 m in circumference. It is noteworthy for 13 cups hollowed out of its upper surface, thought to be relics of prehistoric worship. Composed of orthogneiss/gneiss *œillé* (augen gneiss), this erratic is also thought to be derived from pre-Triassic crystalline basement (the Siviez-Mischabel nappe) of Valais. It sits on the upper Thonon terraces (*see below)* (Perret 2014).

The Pierre d'Amour, also gneiss, stands in Lake Geneva, just offshore from Thonon-les-Bains, and is said to be the local equivalent of 'Lovers Lane', being the goal for romantic walks.

Although these large examples are eye-catching, gneiss is ubiquitous in the boulder clay and interesting smaller examples of this and other 'foreign' material can be seen in local walls,

Figure 8 Building stones of (a) fine-grained and (b) coarse-grained felsic igneous rock used in walls in Le Loyer and Roverée.

and even in pebbles on tracks and beaches. Examples can be found of felsic and mafic igneous rock (Fig. 8); and in blocks of schist and gneiss in walls of local buildings (Fig. 9, *opposite*) there are many greenschist blocks such as these in a wall at Yvoire (Fig. 10, *opposite*); and in blocks of sedimentary rock like these walls in Le Loyer and in Brenthonne church tower (Fig. 11, *page 46*).

Lumps and bumps: terraces, kames and moraine

Working backwards from finding such a wealth of diverse erratic material I began to search for less obvious evidence of glaciation and checked the literature for features left behind as the Rhône Glacier, and in particular its southern tongue, retreated at the end of the Last Glacial Maximum.

Figure 9 Garnet schist (above, left and right): (a) Rouelbeau castle and (c) a house in Le Loyer; and gneiss erratic material (below, left and right): (b) on a track in Le Loyer and (d) the Pierre á Martin.

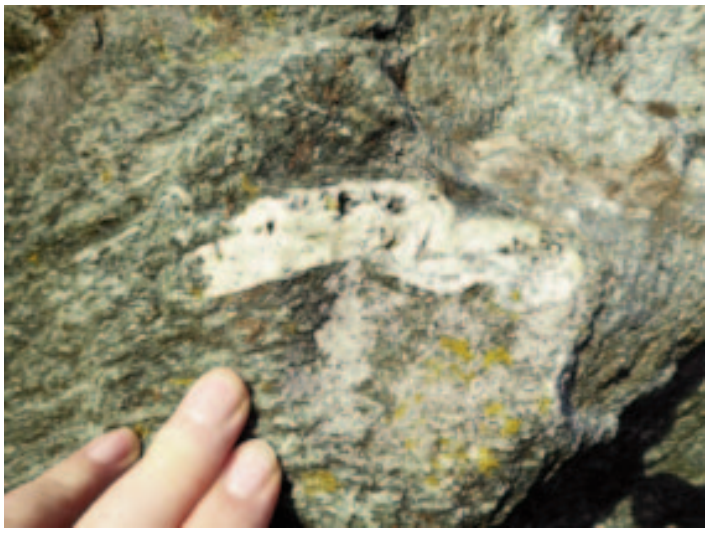


Figure 10 (above, left and right) Greenschist blocks in a wall, Yvoire.

Terraces

During the 19th century there was debate about the lacustrine (delta or shoreline) or glacio-lacustrine (kame terrace) origin of terraces at 3 m, 10 m and 30 m above Lac Leman. Studies by Gagnebin (1937) have since shown that the most recent terrace deposition occurred in 14 stages during retreat, and these features are known as the Thonon terraces (Fig. 12, *overleaf*). The southern side of the Rhône Glacier was confined by the slopes of the Chablais Alps and, as the glacier melted and retreated, banks of sand and gravel derived from lateral moraine were deposited as kame terraces between the lateral margins of the glacier and the adjacent hillsides of the Pre-Alpes. This was towards the end of the last Ice Age, at the end of the second phase of the Last Glacial Maximum; a mammoth tooth retrieved from a quarry has been C^{14} dated at 14 000 years BP (Vial 1975). The Thonon terraces, together with the Evian impluvium, are one of the Chablais Geopark's internationally important sites, but despite this, there is commercial exploitation for construction material (Fig. 13, *overleaf*). Farther up, the Dranse Valley road cutting exposes better consolidated gravels dating from the Riss glaciation, the penultimate glaciation to affect the area (Fig. 14, *overleaf*).

Figure 11 Blocks of sedimentary rock in walls: above (a) Oligocene grit, Le Loyer, and (b) limestone, Brenthonn; below (c) coarse sandstone with liesegang rings, Le Loyer, and (d) cross-stratified sandstone, Rouelbeau

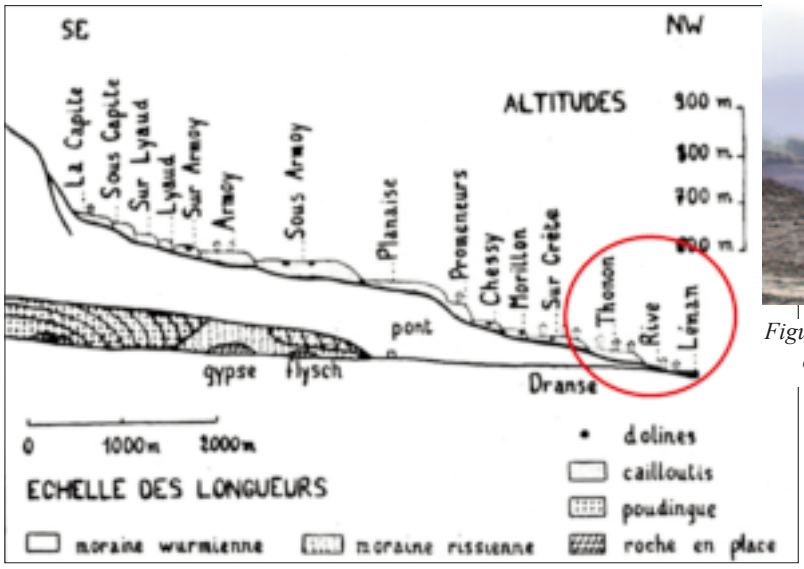


Figure 12 The Dranse Terraces at Thonon (adapted from Croset 1954). The town centre stands on the Thonon Terrace, the funicular rises from 'Rive'— the lake bank. The gorge of the River Dranse has cut through the terraces, providing exposures.

Figure 13 Terrace gravels are commercially, and controversially, exploited in this 500 m long quarry at Lyaud, south of Thonon.

Figure 14 A tunnel on the D902 'Route des Grandes Alpes' in the Dranse Gorge south-east of Thonon cuts through earlier Riss age conglomerates — the Dranse Puddingstones. (Google Streetview imaged 2016).

Figure 15 The town of Bons-en-Chablais is built along the top of a kame terrace: the road winds up the short, but steep, slope outlined in white, and pedestrians have a flight of steps to climb (yellow).

Kame terraces

These are typically more linear deposits. The main street (D903) of my home town of Bons-en-Chablais is built on a kame terrace formed during glacial Stage 3 (*see* Fig. 4). A level road from the north (the D20) suddenly ascends a steep slope to reach this kame, and is steep enough that houses with front doors opening onto the main street have their cellars at ground level on the downhill side; and that a new pedestrian route needed some flights of steps, with an accompanying ramp, built into the path up the 12 m climb (Fig. 15). In Thonon-les-Bains the town centre stands on the Stage5/Stage 6 Thonon Terrace and a funicular railway, built in 1888, rises up these from the River Terrace at the quayside (Fig. 16).

Hollows: meltwater channels and marais

The kame terrace at Bons-en-Chablais is the upstream end of a meltwater channel that carried water flowing to the south-west from this southern arm of the Rhone Glacier. The channel is visible in the landscape as an unusually steep-sided, flat-bottomed valley, and it was this abnormal topography that alerted me to it initially.

At the upstream end of the channel, Google Earth terrain view shows a slight, but definite, ridge running north-west from Bons, on which the hamlets of Chez Moachon and Le Loyer are built (Fig. 17). This is the coarser, better-draining, moraine material, from which the finer particles have been removed by millennia of rain, on which my house sits. It is easier to see the ridge from the north-east when it is clear that the houses are built on this higher ground. This ridge marks a pause in the glacier's retreat north-eastwards during Stages 2 and 3 (*see* Fig. 4).

A meltwater channel, now occupied by the Coudray Brook, winds south-westward, downstream from this point, past the village of Brens, to Machilly (Fig. 18, *overleaf*). The level channel floor has been filled with poorly drained glacial deposits, on which *marais* (marshes) have developed. One of the *marais* was dug out in 1977 and flooded, creating Machilly Lake, partly as a local amenity area and partly to aid regulation of the River Foron, which flows downstream from this point (Fig. 19, *overleaf*). The 30 000 m^3 of mud extracted was used to landscape the area. The railway track between Bons-en-Chablais and Machilly stations takes advantage of the gentle and regular downhill gradient of the channel, as can be seen in Figure 18.

A second meltwater channel a few kilometers north, at Chilly (*see* Fig. 1), ran between the main Rhône Glacier and the northern flank of the Mont de Boisy before depositing sediment in a delta at Veigy. This channel is now also partly occupied by marshland, and is one of the Chablais Geopark's geosites (Fig. 20, *page 49*).

Figure 16 (a) and (b) The funicular railway at Thonon les Bains rises from the lowest, Rive Terrace on the lakeside, to the Thonon Terrace on which the town centre stands (photograph by Howard Ashton-Jones, LRPS).

More hollows: kettle holes

The area around Lyaud, on the edge of the upland ridge south east of Thonon (*see* Fig. 1) is particularly well-known for its *vouas*, the local name for kettle holes. The term *voua* is derived from the dialect name for a damp, grassy meadow and many of the *vouas* are now just that, although some are occupied by small lakes. They lie on the Lyaud terrace (*see* Fig. 12), one of the upper Thonon terraces, which was formed *c.* 27 000 years ago during the Geneva stage retreat. Huge blocks of ice, remnants of the retreating glacier, were left along the glacier's margin, thickly draped with terrace gravel. As the ice blocks melted the gravels sank, leaving deep depressions (Fig. 21, *page 49*) that now mark the SW–NE line of the Lyaud Terrace (Fig. 22, *page 50*).

Figure 17 Le Loyer from the north-east: the ridge of moraine, capped with houses, rises fromlevel pasture.

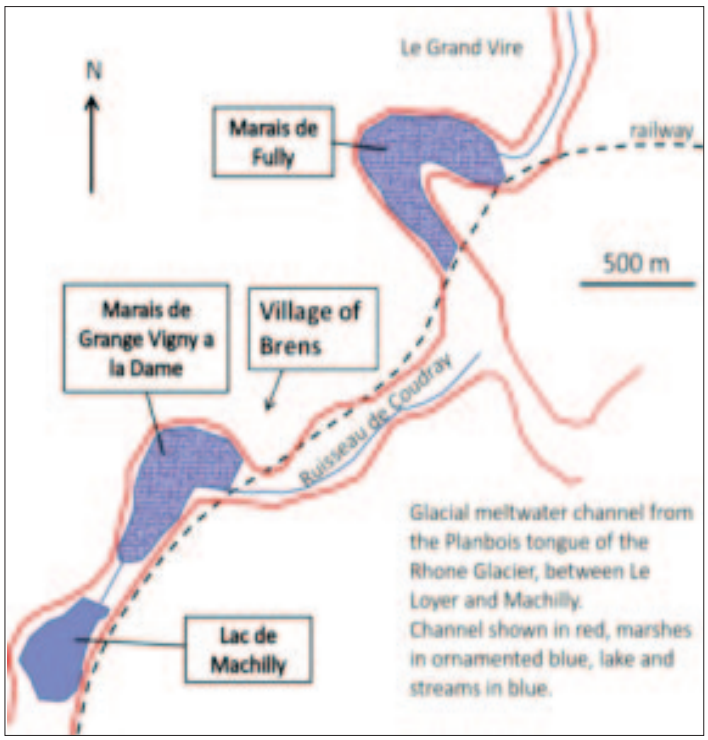

Le Grand Vire
N
Marais de Fully
railway
500 m
Marais de Grange Vigny a la Dame
Village of Brens
Ruisseau de Coudray
Glacial meltwater channel from the Planbois tongue of the Rhone Glacier, between Le Loyer and Machilly.
Channel shown in red, marshes in ornamented blue, lake and streams in blue.
Lac de Machilly

Figure 18 Sketch map of the Coudray Valley between Bons en Chablais and Machilly, showing the location of two areas of marais*, and Machilly Lake.*

The bits the ice missed: molasse inliers

Two inliers of molasse have figured in this account and were going to be upset if they were left out, as they had a role to play in the area's glaciation. The hills at Boisy and Allinges are erosion-resistant beds of grit and conglomerate, of Aquitanian, dated 23.0 Ma–20.44 Ma, and Lutetian–Priabonian, dated 47.8 Ma–33.9 Ma, respectively. These hills separated the main Rhône Glacier from the tongues of ice to its south-east.

As well as being the resting place of the Pierre á Martin, the Mont de Boisy is home to vineyards that produce the crisp, dry white AOC Savoie-Crépy wines (Fig. 23, *page 50*). The hill itself is an inlier of Aquitanian molasse, a mix of conglomerate, limestone and sandston, and 28 000 years ago the north-western slopes of the hill were completely coated with poorly sorted moraine as the glacier began to retreat. The moraine was washed downhill, building up on the hillsides and, over time, the finer element was washed out, leaving a coarse, permeable, substrate ideal for growing vines.

The hill at Allinges is best known today for its old and new castles, and for stunning views north across Lake Geneva. The bedrock is Lutetian–Priabonien, dated 47.8 Ma–33.9 Ma, polygenic conglomerate with sandstone, part of the Upper Flysch '*Serie de Vouan*'. In the past this was a prized source of the raw material for millstones and traces of their excavation can be seen on the sides of the hill (Fig. 24, *page 50*). It is also reported that the conglomerate contains clasts of amber, *allingite*, but these are said to be extremely hard to find!

Figure 19 The Coudray Valley occupies the meltwater channel below Bons -en-Chablais: (a) above Brens the channel cuts down through boulder clay deposited as the glacier retreated — on the left this is capped by kame terrace gravels; (b) still above the village of Brens the valley has silted up, leaving a flat valley floor, now farmed, and steep sides, which are a mixture of grazing, woodland and orchards; (c) the Marais de Grange Vigny a la Dame below Brens is natural marshland in the channel; (d) at Machilly the marsh has been excavated to form a lake and leisure area — the lake helps to control water flow in the Foron River below this point.

Figure 20 The Chilly channel, looking upstream across marshland towards the Mont de Boisy.

Summary

After initially dismissing my local geology as having 'no real rocks', investigation revealed an intriguing story of the ways that glaciation sculpted a molasse landscape, leaving evidence of glacial retreat, and also of how the geology and the resulting geomorphology was used by people as the area was populated after the last glacial period. Nowadays erratic rocks are used as practice crags by climbers; the soil has affected the region's agriculture, while landscape morphology has dictated land use for farming, industry, building, leisure and communications.

However, the more I got to know the area, the more it raised questions that I am keen to explore further: the Rhône Glacier retreated from Bas Chablais 12 000 years BP, but it has not disappeared completely. Its vestiges, measured at 7.65 km in 2016, are still one of the Alps' longer glaciers, but in the intervening 12 000 years it has retreated about 155 km, completely disappeared from the main valley in the last 150 years and now only occupies a hanging valley. Did the glacier retreat regularly, or in stages? I suspect its initial retreat was rapid, well before any settlement of the valley, which is now populous and industrialised as far as the town of Brig. Farther up the valley it is rural and quiet, but is that a result of much later deglaciation of the upper valley, or was it dictated by the presence of trade routes such as the Simplon Pass over the Alps between Switzerland and Italy? How does retreat correlate to changing precipitation and temperature patterns over the centuries? There was a small advance in the 1980s, but in the last 20 years I have seen the ice front retreat farther upstream from the lip of the hanging valley, leaving a hollow now occupied by a pro-glacial lake (Fig. 25, *overleaf*).

References

BRGM 2021 Visualiseur Infoterre. https://infoterre.brgm.fr/viewer/ (accessed 7-12-2021)

Coutterand, S. 2010 *Étude géomophologique des flux glaciaires dans les Alpes nord-occidentales au Pléistocène récent. Du maximum de la dernière glaciation aux premières étapes de la déglaciation*. Géographie: Université de Savoie, 2010

Croset, P. 1954 'Le Piedmont des Dranses du Chablais'. *Revue de géographie alpine* **42**, 521–56: DOI: 10.3406/rga.1954.1144

Gagnebin, E. 1937 'Les invasions glaciaires dans le bassin du Leman'. *Bulletin de la Societe vaudoise des sciences naturelles (Lausanne)* **60**, 29–62

*International Chronostratigraphic Char*t (n.d.). https://stratigraphy.org/ /timescale/ (accessed 14-12-2021)

Perret, A. 2014 'Géopatrimoines des trois Chablais: identification et valorisation des témoins glaciaires', **266**. http://www.unil.ch/igul/home/menuinst/les-publications/geovisions/geovisions-45.html

Sauter, M. R., and Spahni, J.-C. 1949 'Révision des dolmens de la Haute-Savoie (France)'. *Archives Suisses d'anthropologie générale* **14**, 151–67. http://archive-ouverte.unige.ch/unige:95694

Vial, R. 1975 'Le Quaternaire dans le Bas-Chablais (Haute-Savoie). Les derniers episodes de retrait glaciaire'. *Geologie Alpine* **51**, 129–44

Figure 21 (a) The Voua de Lyaud (the kettle hole closest to the parking flag in Fig. 20), and (b) a 'dry'kettle hole just to its north.

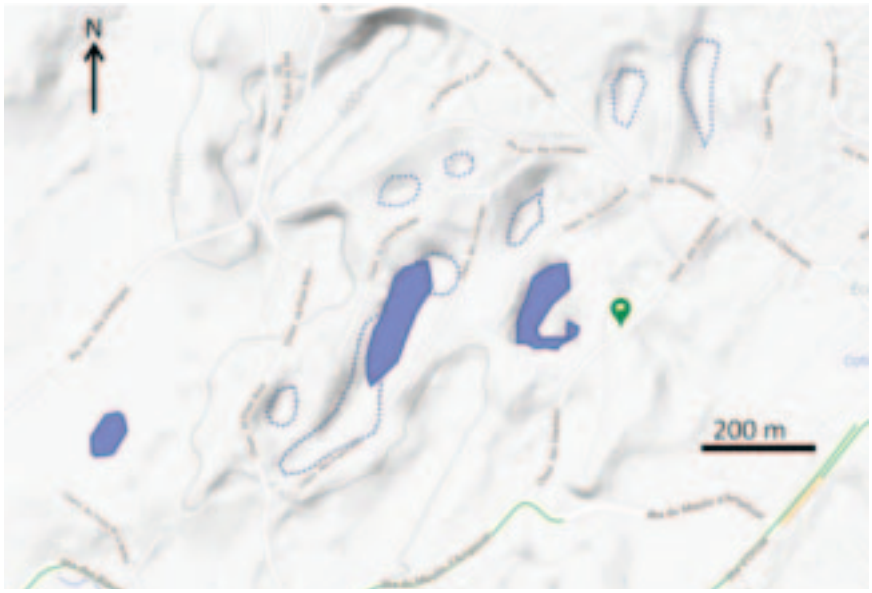


Figure 22 The Lyaud vouas: flooded in blue; other kettle depressions dotted outline (green and white flag = parking) (adapted from Google Earth terrain view 2021).

Figure 23 The Crépy vineyards have been developed on the residue of moraine that coats the northern flank of the Mont de Boisy.

Figure 24 (a) The road up Allinges hill to the new castle. There are exposures of conglomerate and grit by the road and (b), below the castle itself; and it is possible to see where millstones, over 1 m in diameter, were being excavated, but abandoned at (c) and (d).

Figure 25 The Rhône Glacier in summer 2021; in 2000 it covered the entire area now occupied by its pro-glacial lake.

Lockdown geological memories: an unplanned visit to the Petrified Forest near Calistoga, California

John Iley

For many people the UK Government's lockdown in 2020 was a time for reflection on the good times in the past when we could travel more freely. In this context I have put together a short article about an unplanned visit to the Petrified Forest near Calistoga in northern California in 2012. We came across this forest unexpectedly while touring the vineyards of the Napa Valley (Fig. 1).

Figure 1 Key locations (© Microsoft® BingTM Maps. Microsoft product screen shot(s) reprinted with permission from Microsoft Corporation (accessed from Bing Maps website 10 February 2022 and used in this publication in compliance with "Microsoft Bing Maps Platform APIs Terms Of Use" and for educational purposes only).

The forest lies close to Mt Saint Helena, which lies in the Sonoma Volcanic field (USGS 2013). Pliocene (5.33 Ma to 2.58 Ma) volcanism is thought to have been the source of an avalanche of ash, a pyroclastic flow that may have felled and buried the trees. The petrified treetops point in a south-west direction, away from Mt Saint Helena (Petrified Forest Trail Guide) and this led to a hypothesis that volcanism around Mt St Helena was the ash source. This is comparable to the felling of trees when Mt Saint Helens erupted in Washington State in 1980. A direct blast due to a massive sector collapse on Mt Saint Helens felled trees over an area of 16 km^2 (Karowe and Jefferson 1987).

Dissolved silica is required to petrify trees. This can arise through groundwater percolating through volcanic ash and solubilising silica. Instant burial by volcanic ash helps prevent decay by the exclusion of air and attack by insects and fungi.

In this region the Sonoma volcanics are a feature of the solid geology and reflect different eruptive styles (Howard 1979). The volcanics overlie the San Pablo Group of marine sandstones and shales, which were deposited in the Miocene (23.03 Ma to 5.33 Ma). A marine embayment possibly extended from present-day San Pablo Bay in the Miocene, hence the name San Pablo Group. Interestingly, at the Petrified Forest museum there are fossilised fish and shells along with petrified worms, snails and clams, indicating a marine environment at some stage. The Sonoma volcanics probably erupted from several vents over a period of one million years. Ash flows and pumice beds mantle the landscape; and other features include dykes, lahars, breccias and volcaniclastics.

Before visiting the petrified forest itself a clue to the local geology can be seen in the building stone of the Rhine House at the Beringer Vineyard (Fig. 2). The building stone is lithified vesicular volcanic ash known as tuff. Despite having lots of air-filled vesicles, it has sufficient strength to be used in the building.

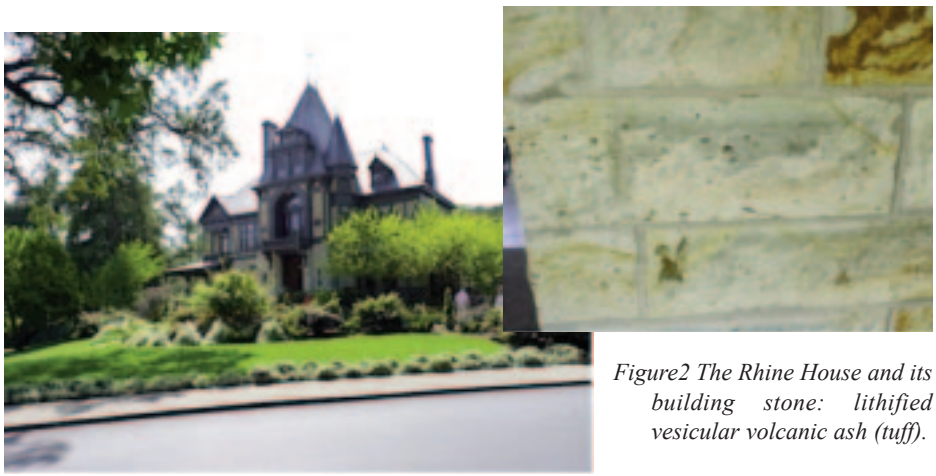


Figure2 The Rhine House and its building stone: lithified vesicular volcanic ash (tuff).

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Figure 3 The Petrified Forest Visitor Center.

After arriving at the Petrified Forest Visitor Center (Fig. 3), we were given excellent trail guides, which showed the location of the petrified trees. The petrified trees are mainly Californian Coastal Redwoods, but also include oaks and pine trees. Unidentified prehistoric redwood trees are often termed *Sequoia langsdorfii*. Identification can be established if cones can be found. Of the coastal redwood the most well known is *Sequoia sempervirens*, which can live for 1200–2200 years or more and grow up to 115.5 m high, and up to 8.9 m in diameter.

The forest lies close to the Silverado Trail, which was used in the 1800s by miners to travel to the silver and cinnabar mines. While on his honeymoon, Robert Louis Stevenson visited the forest, and a plaque commemorates his famous meeting with Charles Evans who discovered the forest in 1871 (Fig. 4). The petrified forest is mentioned in Stevenson's book (1906) *The Silverado Squatters*.

Excavation of the petrified trees goes back to 1914, and interestingly part of the 50¢ admission fee charged when the forest was first opened to the public was used to pay geology students to help excavate the trees. Examples of the petrified trees are shown in Figures 5 and 6.

Looking more closely at the mechanism of petrification, laboratory studies have been carried out to try and reproduce the silicification of wood (Ballhaus *et al.* 2012). This has been successful by adding Pseudotsuga wood to a hot alkaline aqueous solution of ground obsidian as the silica source. Dissolution of silica requires alkaline conditions and precipitation requires acid conditions. Lignin and other compounds in the wood release hydrogen ions, which trigger the precipitation of silica. Opal microspheres were found in a tracheid (cylindrical, tapered cell in a plant trachea, the tube-like non-living cells in plant xylem, Allaby 1992) and was confirmed by scanning electron microscopy (SEM). It has been estimated from the studies that timescales for the petrification of large trees are on the order of 1000s of years. Figure 7 shows a fragment of petrified wood brought back from the forest, showing a high level of preservation.

Figure 4 Plaque commemorating the famous meeting of Robert Louis Stevenson and Charles Evans known as 'Petrified Charlie'.

Figure 5 'The Giant'.

Figure 6 'The Queen'.

Figure 7 Fragment of petrified wood from the Calistoga Petrified forest.

Another fragment of petrified wood, probably from the Chinle formation (Triassic) in northern Arizona, near Cameron shows a similar high level of preservation on a micron scale (Fig. 8). This is an end view of an unpolished petrified wood fragment in its natural state, photographed by W. P. Armstrong in 2011 using a macro lens. The average diameter of one tracheid cell lumen in the cross section is *c.* 30–40 µm, which is beyond the resolution of the human eye. More information on this photograph can be found in the weblink shown in the caption of Figure 8.

Figure 8 Specimen of preserved Tracheids,image source (www2.palomar.edu/users/warmstrong/fossil.htm#cameron).

In summary the visit to the [Calistoga] Petrified Forest provided a fortuitous excursion to the wine tour of the Napa Valley. However, a word of warning for anyone planning a visit, look out for rattlesnakes (Fig. 9)!

Figure 9 A California rattlesnake: Crotalus oreganus.

References

Allaby, Michael (ed) 1992 *The Concise Oxford Dictionary of Botany*. Oxford UP

Ballhaus, C., Gee, C. T., Bockrath, C., Greef, K., Mansfeldt, T., and Rhede, D. 2012 'The silicification of trees in volcanic ash — an experimental study'. *Geochimica et Cosmochimica Acta* **84**, 62–74

Karowe, A. L., and Jefferson, T. H. 1987 'Burial of trees by the eruption of Mt St Helens, Washington: implications for the interpretations of fossil plants'. *Geol Mag* **124** (03), 191

Howard, A. D. 1979 *Geologic History of Middle California*. Berkeley: UCal Press

Petrified Forest Trail Guide: www.petrifiedforest.org (accessed 2020)

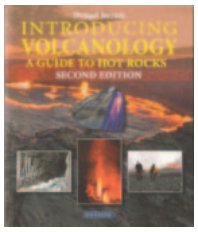
Savidge, R. A. 2007 'Wood anatomy of the Late Triassic trees in Petrified Forest National Park, Arizona, USA, in relation to Araucarioxylon arizonicium Knowlton 1889'. *Bull Geosci* **82**, 310–28

Stevenson, R. L. 1906 *The Silverado Squatters*. London: Chatto and Windus

USGS National Geologic Map Database 2013 'Preliminary geologic map of the Calistoga 7.5 — Quadrangle, Napa and Sonoma Counties, California: a digital database, California Geological Survey

(An earlier version of this article was originally published in the North West Branch Newsletter May 2021 — Editor.)

Book review



Jerram, Dougal 2021 *Introducing Volcanology: a Guide to Hot Rocks* (2nd edn). Edinburgh: Dunedin Press (ISBN 978-1-78046-090-1; xi + 139pp; paperback £9.99)

Dougal Jerram, 'Dr Volcano' of television fame and DougalEARTH is obviously quite a character. He has, for example, travelled down the Grand Canyon in a wooden boat, and explored the lava lake of Erta Ale in Ethiopia. He presents complex information with a natural teacher's ease of familiarity.

This revised and updated edition of *Introducing Volcanology* follows the ten-chapter format of the first edition. The glossary is helpful and concise, and serves as an informal index to the book.

The first Chapter, 'World of volcanoes' sets the scene for what is to follow. 'The Cooling Earth — How rocks melt' and 'Volcanoes, tectonics and planets' develop the topic further. In figure 2.2 'Dr Volcano's guide to melting rocks' we learn the melting point of Granite flakes (750˚C) and Basalt-a-bix (1150˚C), a lightness of touch that characterises Jerram at his best.

'Types and Scales of Eruption', 'Lava flows and bubbling cauldrons', 'Explosive pyroclastic eruptions and their deposits' cover much that will be familiar to OU geology students and OUGS members. There also is a chapter on 'Igneous intrusions — a window into volcanic plumbing'. In the preface Jerram mentions the late Henry Emeleus at whose feet many of us sat, and the section 'Fossil magma chambers' is a fitting tribute to h Emeleus' is work in the Hebrides, particularly Rum and the Adjacent Islands.

As in the first edition, I think it is the later chapters that make this book so interesting. 'Volcanoes, life and climate', 'Monitoring volcanoes', and 'Volcanoes and man'. In the last chapter the author is pictured with a snow monkey. Now you will need to buy the book to find out why.

I deposited the first edition of this book in a branch library, so do not have it to hand to make direct comparisons. The section on mantle plumes has almost certainly been extensively rewritten. Being picky, they would almost deserve a chapter to themselves; the sections on the Galapagos, Holuhraun, Hawaii (2014–15), Kilauea (2018) and Stromboli (2019) are new.

There are a couple of errors, which will need to be corrected in the third edition: Diapirs (p77) becomes Diapers (p129) in the glossary. Herculaneum (p109) has an alternative spelling in Fig. 10.4.

Another area for improvement could be some uniformity in the explanations accompanying the figures. Although most are expanded in the text, it would be so useful to have the explanatory material alongside the diagram. This is particularly true of Fig. 4.3 'Types of eruption', which all look very similar unless you read the text; also of Fig. 2.3 'Bowen's reaction series'. Some of the illustrations would benefit from enlargement. Do not misunderstand me: This is a very good book, which could be made even better.

Reviewing the first edition of this book for *OUGS Journal* (Vol 33 No 1 2012, p26) I wondered if it was worth the cover price. It is ten years since the first edition was published, and given that prices have risen greatly in ten years, and that this slim volume is thicker and updated, I have no hesitation in saying that it is worth every penny. Introductions at undergraduate level fall into two categories: short introductions, and long, sometimes very long and dull ones. This book is short, but not trivial. It is certainly not dull. Any chapter of this book could be expanded to form another book in the same genre. The pictures alone earn a place on your bookshelves.

— Peter Blackett BSc (Open), Northumbria OUGS

Book review

Sensarma, J. and Storey, B. C. (eds) 2018 *Large Igneous Provinces from Gondwana and Adjacent Regions*. London: Geological Society Special Publication 463 (ISBN 978-1-78670-32540, ISSN 0305-6719; 278pp; hardback £140)

There are 11 main sections and a index:

Ch 1 Gondwana Large igneous provinces — LIPs — distribution, diversity and significance
Ch 2 plate reconstructions, volcanic basins and sill volumes
Ch 3 Ferrar LIP: field and geochemical constraints on supracrustal (high level) emplacement of the magmatic system
Ch 4 The Panjal Traps
Ch 5 mantle source heterogeneity in continental mafic LIPs – insights from the Panjal, Ramjmahal and Deccan basalts (India)
Ch 6 Imprints of modal metasomatism in post Deccan subcontinental lithospheric mantle ….
Ch 7 Origins of Amba Dongar carbonatite complex — India
Ch 8 Mineralogy, geochemistry and geochronology of mafic magmatic enclaves etc
Ch 9 Regional volcanism of northern Zealandia post Gondwana break-up magmatism
Ch 10 Modelling basalt weathering at elevated CO_2 concentrations
Ch 11 Geochemical and Sm-Nd isotopic constraints on the petrogenesis and tectonic setting of Proterozoic mafic magmatism of Gwalior Basin Central India
Index

Each chapter starts with its list of contributors and a comprehensive abstract. At the end of each chapter there is a comprehensive list of references. There are plenty of tables, colour and black and white diagrams, stratigraphic charts, cross-sections, photos, location and geological maps, geochemical and element analyses, methods, results and discussions.

A large part of the book concerns India, although Northern Zealandia and the Antarctic are also discussed in some detail.

— Rosemary Darby, OUGS, BA (Open), BSc Hons (Open) Natural Sciences with Earth Science, Certs Ed UK & NZ

The Banks Peninsula — South Island, New Zealand:-a tale of two volcanoes

Bev Chesterman

The Banks Peninsula, adjacent to the city of Christchurch, protrudes prominently into the Southern Ocean part-way down the eastern seaboard of South Island. When Captain Cook first saw it in 1770 he mistakenly thought it was an island and named it Banks Island after his expedition botanist, Sir Joseph Banks; and indeed it was an island for much of its formation.

Brief summary of New Zealand's geological formation

The two basement blocks of New Zealand both formed from sediments eroded from Gondwana and volcanoes. These blocks were obducted onto the edge of Gondwana in two phases: during the Devonian and during the Early Cretaceous. The latter, the Rangitata Orogeny, formed the Torlesse, the rocks that make up the Eastern Block that today lie to the east of the Alpine Fault. After Gondwana separated from Laurasia it too began to break up. During the Late Cretaceous, as Australia began to break away from Gondwana, so also New Zealand began to break away from Australia (Fig. 1).

Rift zones and fractures provided pathways for erupted andesites and rhyolites, including in a small area many kilometres offshore, in what was to become the Banks Peninsula. Unlike the later volcanic episodes, some of these early episodes were erupted explosively, forming ignimbrites. By the Palaeocene the Tasman Sea was fully open and New Zealand was in its present situation.

For nearly 40 million years New Zealand eroded away until only the drowned remnants of the Rangitata Mountains were above sea level. Then, at *c.* 23 Ma there was further collision and renewed uplift (the Kaikoura Orogeny), bringing together the Western and Eastern Basement Blocks along the length of South Island, either side of the Alpine Fault — a strike-slip fault. The Kaikoura Orogeny created the Southern Alps, which have been eroding fast, with the eroded materials being deposited to east and west. To the east they were deposited across what was to become the Canterbury Plains and far out to sea. The earlier deposits were compacted to form the Charteris Sandstone.

Figure 1 Break-up of Pangaea.

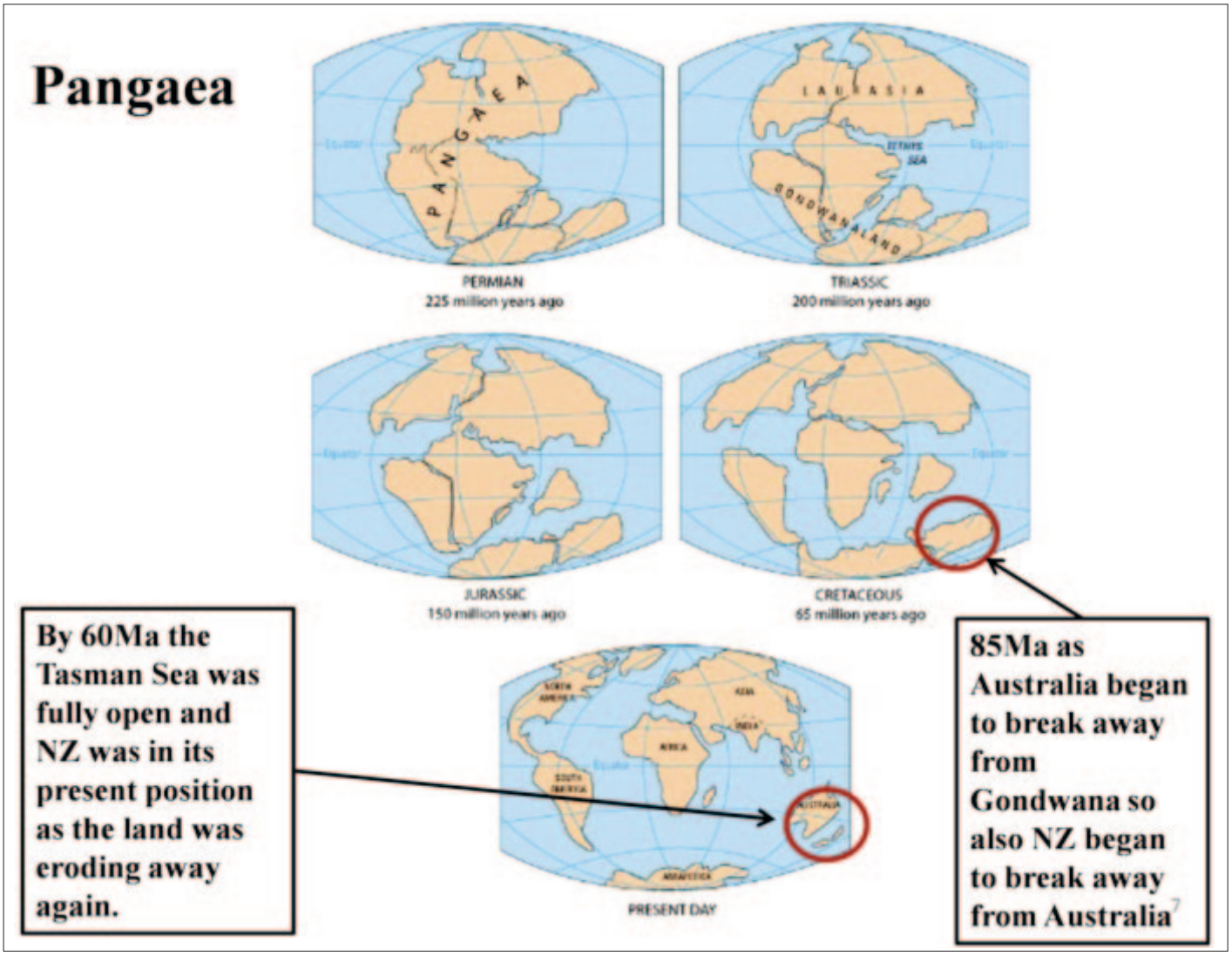

Pangaea
PERMIAN
225 million years ago
TRIASSIC
200 million years ago
JURASSIC
150 million years ago
CRETACEOUS
65 million years ago
PRESENT DAY
By 60Ma the Tasman Sea was fully open and NZ was in its present position as the land was eroding away again.
85Ma as Australia began to break away from Gondwana so also NZ began to break away from Australia

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Figure 2 Banks Peninsula today.

By *c.* 15 Ma, when our story proper begins, the Southern Alps were still eroding fast, still depositing materials far out to sea, and where magmas began to be erupted through the Torlesse sediments, Charteris Sandstone and the Cretaceous andesites and rhyolites. These magmas were erupted over a period of *c.* 10 million years, in five different volcanic episodes. Four of these episodes formed the Lyttelton Volcano and the fifth the Akaroa Volcano, which together make up the Banks Peninsula as we know it today (Figs 2 and 3).

The Lyttelton Volcano

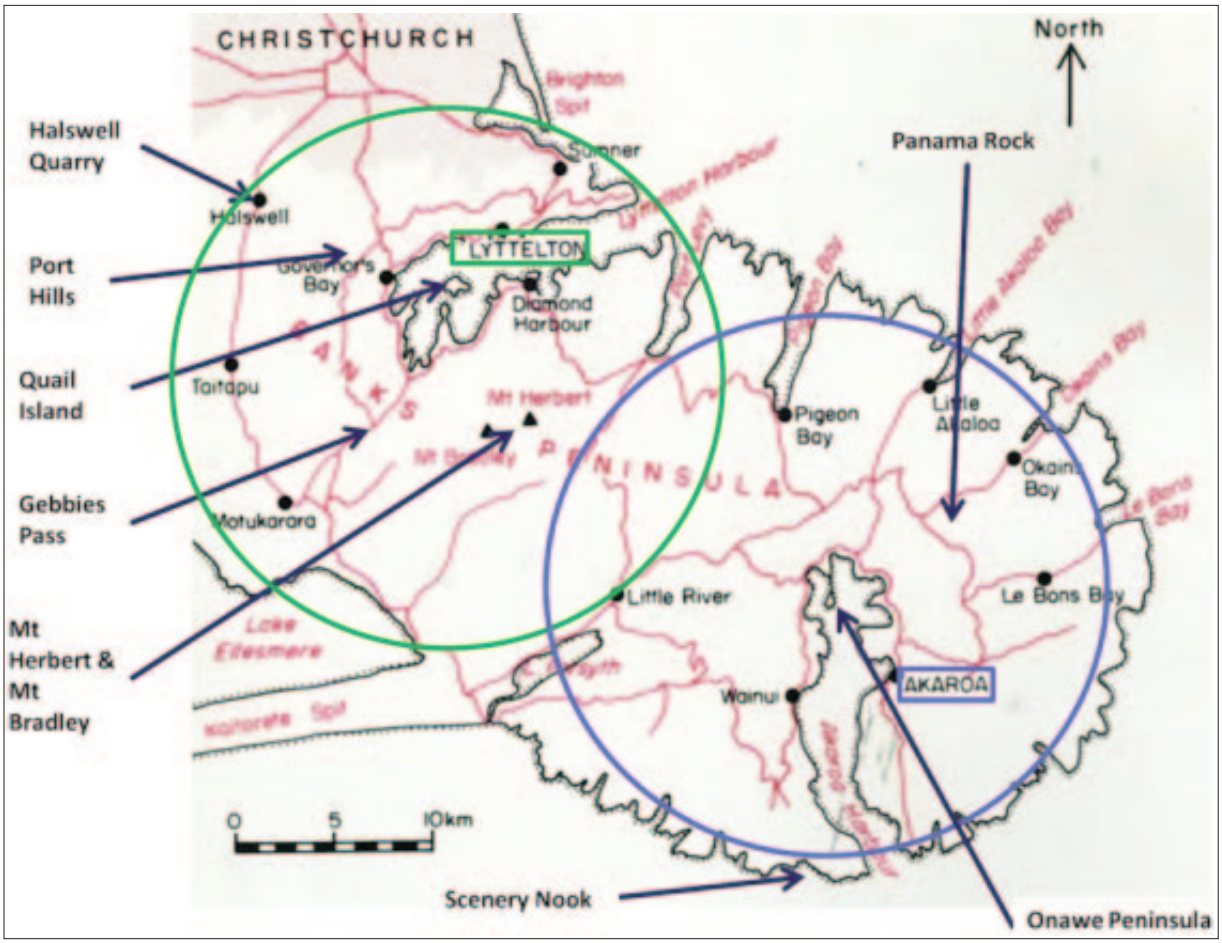
The first of these volcanic episodes was the Governors Bay Volcanics (GBV), which were erupted between 15 and 12 Ma from numerous centres onto the uneven surface of the Palaeocene Charteris Sandstone and the much older Torlesse (Fig. 4a, *opposite*).

Yet these same rocks are found at 1070 m below sea level in a borehole 36 km west in the Canterbury Plains, suggesting that the Lyttelton Volcano is built on a 1 km high mountain of Torlesse rock! These older rocks within the crater mean that the crater that looks so much like a caldera, is not a caldera , but rather an erosion crater. The Lyttelton and Akaroa craters are two of the best examples of erosion craters in the world. An intriguing feature of these much older rocks is that they lie today inside the Lyttelton crater and at an altitude of 300 m (Fig. 5, *opposite*).

The GBV were not very extensive, but they were varied: basaltic to andesitic, but there were also rhyolite domes and lava flows as seen on Quail Island, indicating crustal contamination and not just mantle melting (Fig. 6, *opposite*).

The Lyttelton Volcanics (LV) erupted between 12 Ma and 10 Ma, were more extensive and constructed the main cone of the volcano with a couple of parasitic cones (Fig. 4b). They were mostly dark basalts (hawaiites) but a few of the flows and many of the dykes are trachyte — distilled by fractional crystallisation from the basaltic parent liquid in the magma chamber (Fig. 7, *page 58*).

Figure 3 Banks Peninsula — indicating the extent of the two volcanoes and the different localities mentioned in the text.



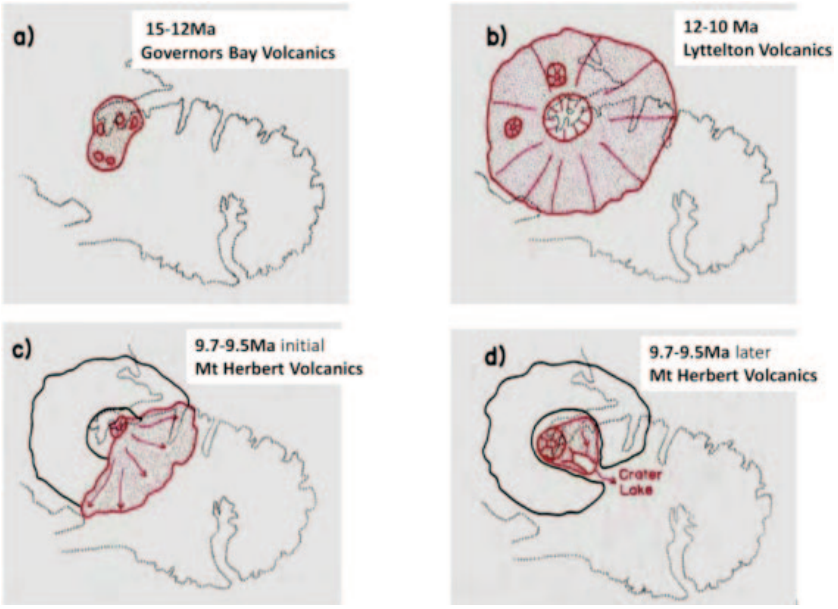


Figure 4 Maps showing where and the extent of different volcanic episodes (part 1).

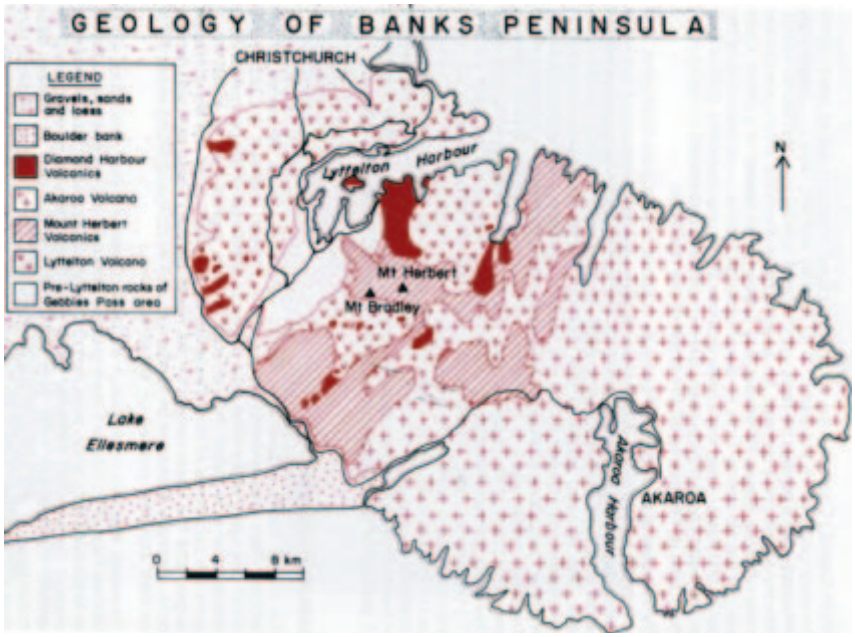
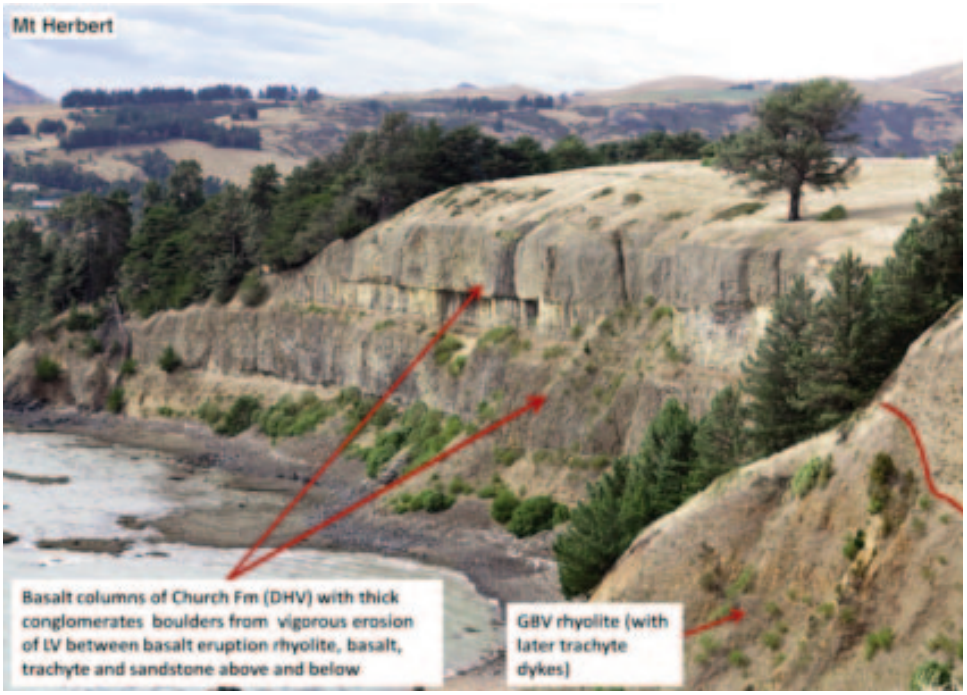


Figure 5 Simplified map of the geology of the Banks Peninsula today.

Figure 6 Quail Island.


Mt Herbert
Basalt columns of Church Fm (DHV) with thick conglomerates boulders from vigorous erosion of LV between basalt eruption rhyolite, basalt, trachyte and sandstone above and below
GBV rhyolite (with later trachyte dykes)

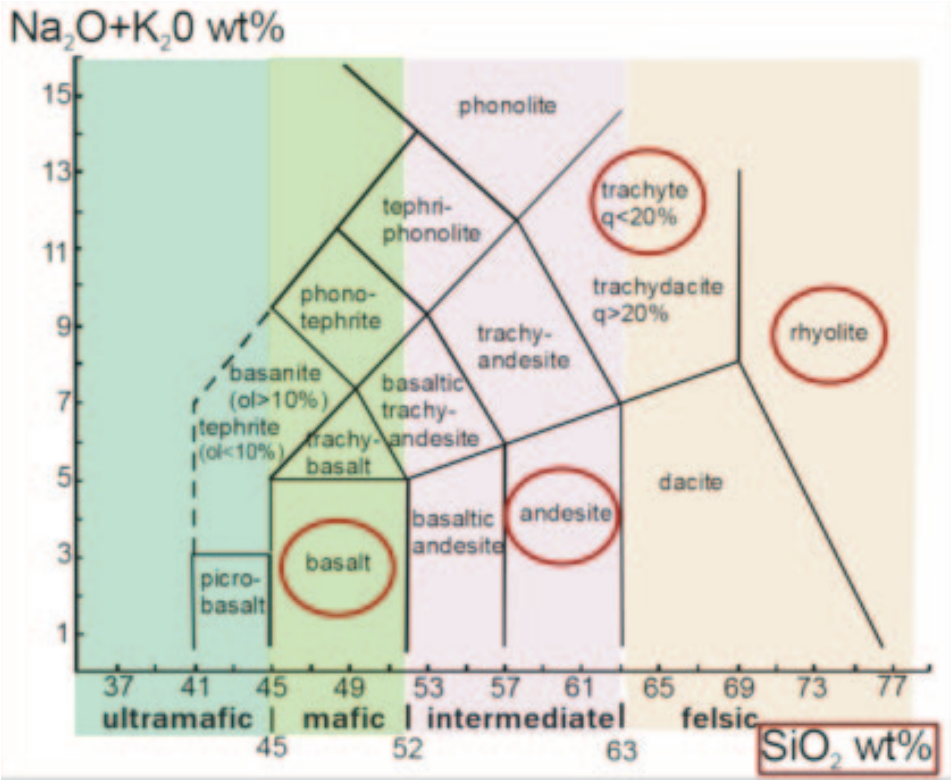


Figure 7 Chart of the compositions of the different types of igneous rock mentioned in the text.

After the LV eruptions ceased the erosion accelerated, breaching the crater wall to the south-east and excavating a deep crater under the site of Mt Herbert today. The initial Mt Herbert Volcanics (MHV) were erupted onto the south-east flank of the eroded Lyttelton Volcano from 9.7 Ma to 9.5 Ma (Fig. 4c). Then activity moved to another centre of eruption within the eroded crater (Fig. 4d). Basalt flowed over the crater floor forming ponds against the south rim. When eruptions decreased a freshwater lake formed within the crater, at *c.* 350 m above present sea level. Periodically eruptions interacted with the water, producing base-surge deposits, which can be seen on the Mt Herbert Walkway.

By 9.1 Ma there were renewed eruptions from the vents in the south-east rim and at Port Levy (to the north-east), causing lava and ash to be spread over what is now the central parts of the peninsula, also filling the breach in the crater wall (Fig. 11e, *opposite*).

Over about the next half million years the thick piles of lava that formed Mts Bradley and Herbert built up. The final eruptions of the MHV occurred from fissures from near the summit of Mt Herbert *c*. 8.5–8.0 Ma (Fig. 11f).

Over the two million years multiple flows built up a symmetrical cone estimated to have been *c.* 1500 m high. Most of these flows were quiet Hawaiian style eruptions with a few more violent Strombolian eruptions from the main vent, and also from the parasitic cones. In a few places some air-fall tuffs can be seen.

A well-developed radial dyke swarm formed as the superstructure domed up and cracked owing to rising magma (Fig. 8). These can be seen at various points around the crater rim; such as Remarkable Dykes on Mt Bradley and Rapaki Rock, and Multiple Dykes along Summit Road in the Port Hills (Fig. 9).

Even as more lava flows were building the cone it was being eroded by streams; meaning many later flows and lahars were channelled into gullies (Fig. 10, *opposite*).

The Akaroa Volcano (9.1–9.5 Ma and 8.5 Ma)

During the dying stages of the MHV the Akaroa Volcanics (AV) began erupting magmas similar to the MHV: primarily basalt, but also trachyte (Fig. 11e). The oldest rocks — trachyte lavas and pyroclastics — can be seen around the inner harbour. Akaroa flows buried parts of the south-east slopes of Lyttleton and interfingered with flows from Mt Herbert, showing that they were erupting contemporaneously for some of the time (Fig. 11f).

These lavas formed the flat-lying columnar-jointed flows capping both Mt Bradley and Mt Herbert (Fig. 12, *opposite*).

Figure 8 Map of the radial dykes in the Lyttelton Volcano.

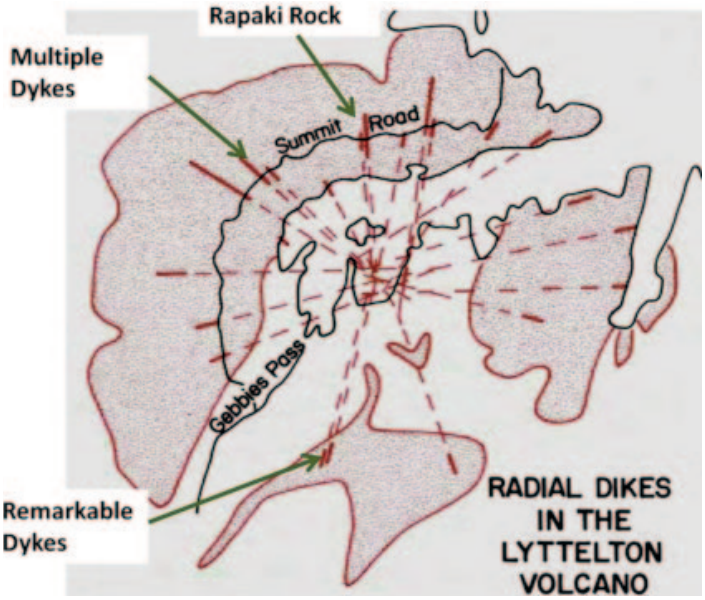


Figure 9 Multiple Dykes, Summit Road, Port Hills (photo by K. Pedley/UC).

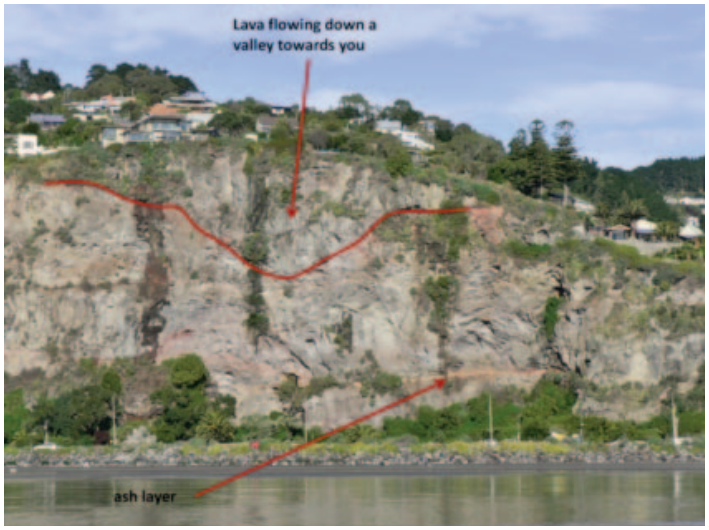


Figure 10 Lava flows and ash band at Peacocks Gallop, Clifton.

The MHV are an intermediate stage in the south-east migration of volcanic activity from Lyttelton to Akaroa.

Similar to the Lyttelton Volcano, the Akaroa Volcano formed a dyke swarm towards the end of its active period, centred just south-east of the Onawe Peninsula, leading to the emplacement of many trachyte dykes, such as Panama Rock (Fig. 13), others criss-crossing the Onawe Peninsula (Fig. 14, *overleaf*), and at Scenery Nook (Fig. 15, *overleaf*).

The growth of the Akaroa Volcano over one million years is much simpler than that of the Lyttelton Volcano, and died out by *c.* 8 Ma. As with the Lyttelton Volcano, the Akaroa Volcano started eroding while it was still growing and this erosion of the inner and outer flanks of both volcanoes continued. A new breach to the south wall of the Lyttelton created the Gebbies Pass by *c.* 8 Ma.

Diamond Harbour Volcanics (7.8–5.8 Ma)

The final volcanic episode was the eruption of the Diamond Harbour Volcanics (DHV) from numerous vents on the flanks of the Lyttelton crater, starting 7.8 Ma (Fig. 11g). The earliest of these were olivine-rich basalts, which flowed down deep valleys cut into the older rocks. Also, a large lava cryptodome formed above what is now Halswell Quarry (Fig. 16, *overleaf*). Later magma intruded through the basalt and ash layers producing the Halswell Stone, fine-grained dense black basalt, which has been extensively used as a building stone in Christchurch for walls, steps and paving.

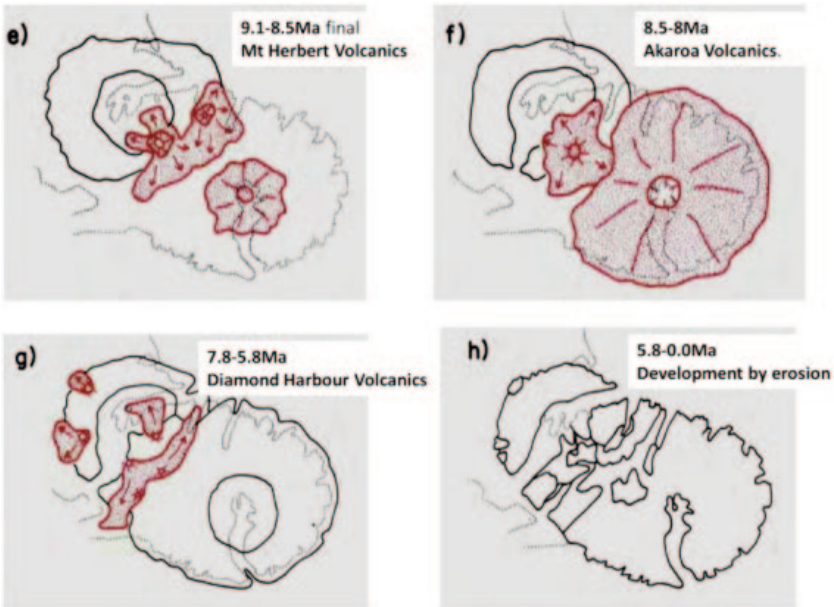


Figure 11 Maps showing the whereabouts and extent of different volcanic episodes (part 2).

Figure 12 Flat-lying columnar-jointed MHV flows capping Mt Bradley as seen from Mt Herbert Walkway.

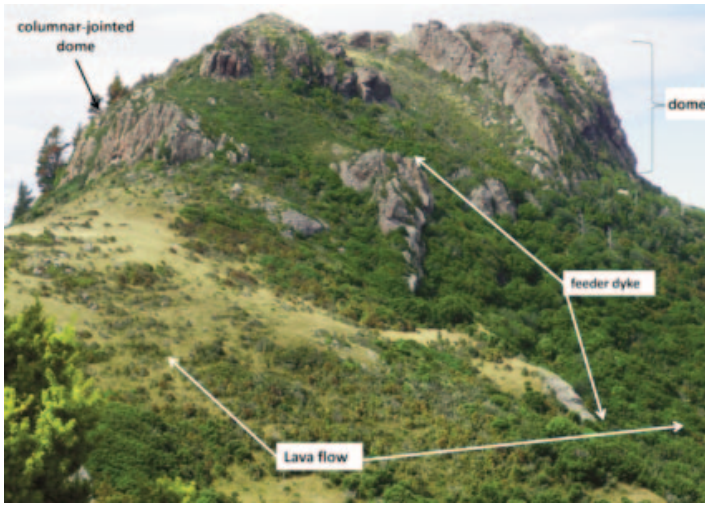


Figure 13 Lava dome and its feeder dyke — Panama Rock, Akaroa (photo by K. Pedley/UC).

Dying embers: development by erosion (5.8–0.0 Ma)

From a fissure vent close to the top of Mt Herbert lava flowed down into the Lyttelton crater and across to Quail Island (*see* Fig. 6). There are more than 60 thin lava flows underlying the smooth dip slope from the summit of Mt Herbert down to Diamond Harbour. The youngest of these is dated 5.8 Ma.

Then, after nine million years of more or less continuous activity, the volcanism stopped. As yet no one knows why the magma formation 60–100 km below the peninsula stopped, nor, indeed, why it started in the first place. Erosion did not stop — creating the modern topography of the Banks Peninsula with its many bays and inlets; and also the great inlets within which the Akaroa and Lyttelton Harbours developed (Figs 17 and 18, *page*, *61*).

Figure 14 Ōnawe Peninsula, Akaroa harbour — trachyte dyke along shore with chilled margin (pale colour at the edges).

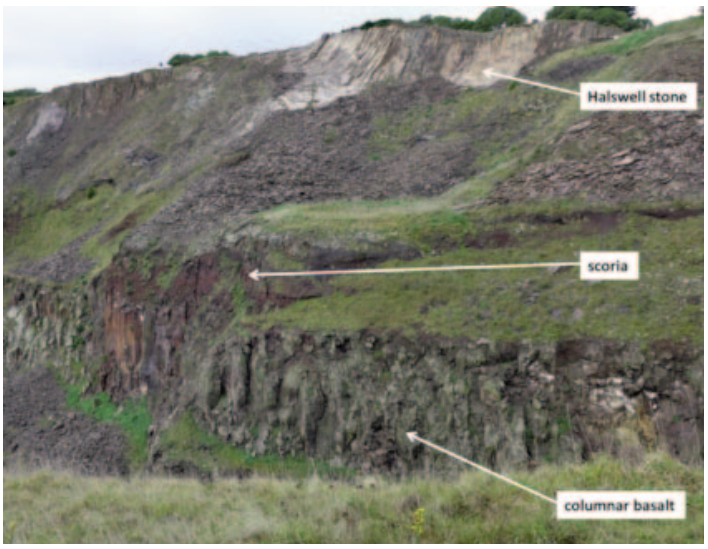


Figure16 Halswell Quarry, Christchurch.

It was only *c.* 20 000 years ago that the gravels from the eroded Southern Alps combined with a small drop in sea level, joined Banks Island to the mainland. About 6,000 years ago, as the glaciers melted, the sea level rose again by a few metres and the Canterbury Plains and the western flanks of the Lyttelton Volcano were buried in loess up to 20 m thick (Fig. 19, *opposite*).

Summary

The Banks Peninsula is formed from two slightly overlapping Miocene erosion craters. These are two of the world's best examples of erosion craters. There were five volcanic episodes over a period of about 10 million years as the eruption centres moved south-east before reverting to the initial area in the dying stages of the volcanism. Most of the material erupted was basalt or trachyte, with some andesite and rhyolite in the earlier eruptions.

Main source

Weaver, Stephen, Sewell, Rod, and Dorsey, Chris 1985 *Extinct Volcanoes: A Guide to the Geology of the Banks Peninsula*. Published by the Geological society of New Zealand, now out of print; but available as a .pdf

Other sources

Coate, Glen 2002 *The Rise and Fall of the Southern Alps*. Christchurch: Canterbury UP

Livermore, Andrew 1999 *Cinder Cones of the Lyttelton Volcano, Banks Peninsula*, NZ (pdf) https://www.geocaching.com/geocache/GC44Y7W_crikey-dike-canterbury?guid=8085b988-9d15-4295-9b60- 2f0db86b93fd

Quail Island: https://porthillswalkers.wordpress.com/2016/03/11/quail-island/

Quail Island: https://www.geotrips.org.nz/trip.html?id=439

Halswell Quarry: https://www.geotrips.org.nz/trip.html?id=272

Ōnawe Peninsula: https://www.geotrips.org.nz/trip.html?id=389; https://www.geotrips.org.nz/trip.html?id=511

Crikey Dike/ Multiple Dikes: https://www.geotrips.org.nz/trip.html?id=717

Sugarloaf (scoria cone): www.summitroadsociety.org.nz https://the-earth-story.com/post/79245901514/scenery-nook-this-small-site-on-the-pacific-ocean

Thornton, Jocelyn 1985 The *Reed Field Guide to New Zealand Geology*. Aukland: Reed Publishing (NZ) Ltd

Figure 15 Scenery Nook, outside Akaroa Harbour — with a trachyte dyke cutting through the softer basaltic scoria, ash and agglomerate layers (photo by Jon Sullivan).

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(An earlier version of this article was originally published in the East Anglia Branch Newsletter June 2021 — Editor.)

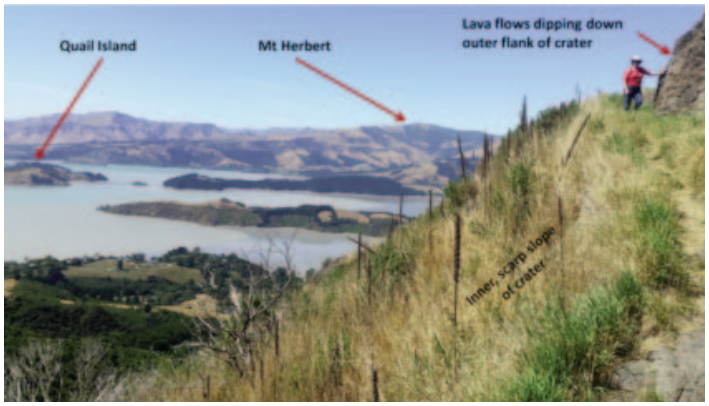
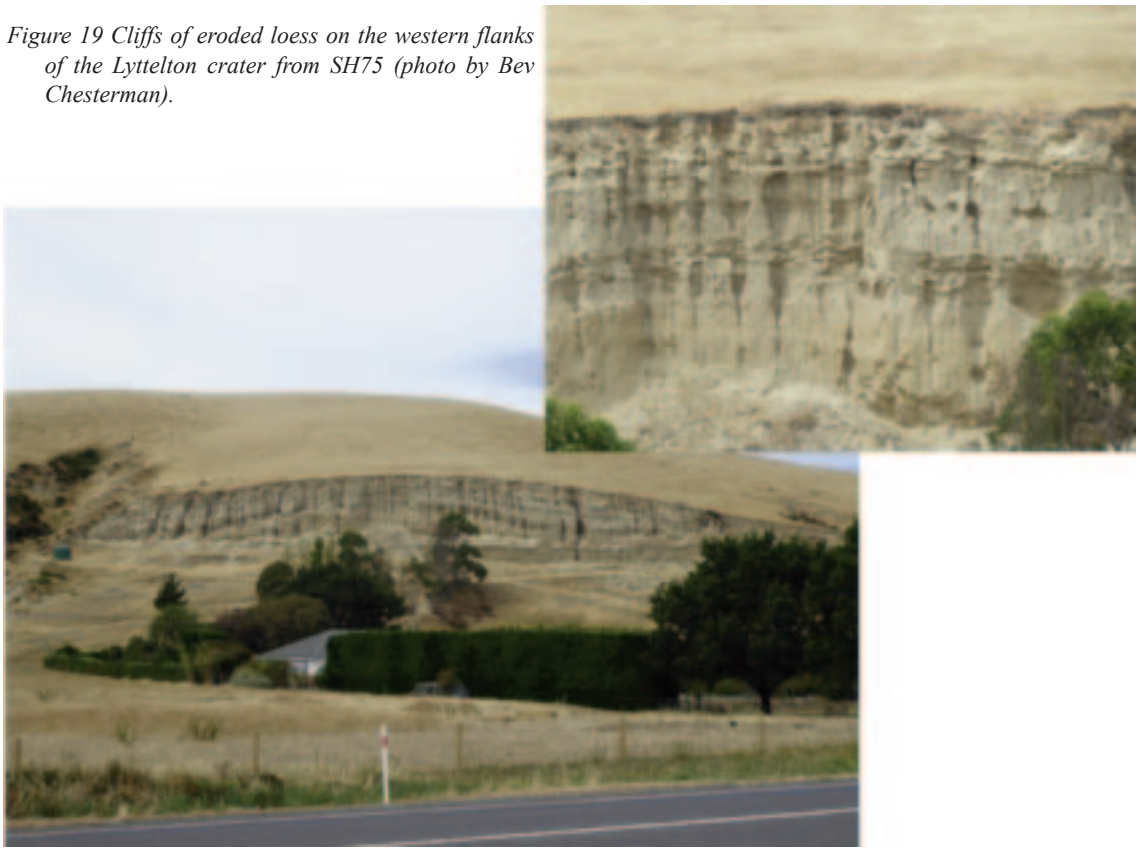


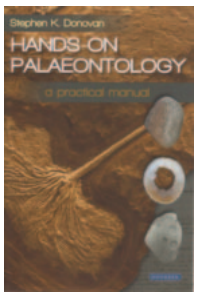
Figure 17 Lyttelton Harbour from inside the crater rim (photo by Bev Chesterman).

Figure 18 Ōnawe Peninsula prominent in Akaroa harbour.

Figure 19 Cliffs of eroded loess on the western flanks of the Lyttelton crater from SH75 (photo by Bev Chesterman).



Book review



Donovan, Stephen K. 2021 *Hands-on Palaeontology: a Practical Manual.* Edinburgh: Dunedin Academic Press Ltd (ISBN 97-8-17804-609-70; I–xviii + 250pp; paperback £18.00)

Prof. Donovan , a palaeontologist and specialist in Caribbean geology, has set out to provide a useful and effective guide for the amateur and undergraduate earth scientist whose interests are palaeontology and fossil identification. There is a large market for such books. In my opinion Donovan's book succeeds admirably.

This is not a book of Introducing palaeontology as a subject, but rather a manual for recognising, collecting, studying, identifying, describing and writing about fossils.

He has arranged his manual in five sections, comprising 53 chapters. Each brief chapter provides perhaps half an hrs to an hour's read of procedure and advice; brief because Donovan guides you a bite at a time. For example, the first three chapters are: 'How to collect', 'Where to collect' and 'What to collect'.

Subsequent chapters describe: how to organise your field notebook to explanations of different fossiliferous rocks; how they are formed; how fossils form in them; what a fossil can tell you about the deposit they are in; different environments in which to collect; common sense in collecting and 'collecting with a camera'; even advice on buying specimens.

A second part explains palaeontology as a science or pursuit. Its chapters cover various ways in which organisms become fossilised; the sorts of geological transport and processes that can affect them; 'burial and diagenesis; and fossil types, such as actual fossilised jbumals and plants, disarticulated specimens, and trace fossils.

Donavan's third section provides a methodology for storage, labelling, photographing, drawing and writing about your fossils. There are also brief chapters on casting and moulds, and on the problems with preservation.

A fourth part offers advice and help on meeting, collaborating and participation with others in your paleontological interest. It consists of chapters on societies, conferences, publications to consult and read, museum collections, and actually publishing on your own fossil specimens.

The final, fifth, part is a 'field guide'. That is, an introductory chapter followed by nine chapters on different places around the world where useful paleontological and fossil-hunting trips can be taken. The locations range from seven in the UK, to one-man the Netherlands and one in Antigua.

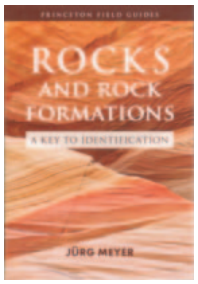
The book finishes with a useful seven-page Glossary and an eight-page Index.

Prof. Donavan's writing is easy and 'familiar'. He *converses* with you about palaeontology and fossil collecting. The book includes 115 photographs, maps, diagrams and charts both min cooler and half-tone. But this is not an identification guide for fossils. Each chapter ends with a reference list for the purpose of giving you an avenue to further information about the practical material he has written and towards identification of your fossil finds.

The book is well produced and will provide an excellent introduction to the fascinating pursuit of fossils finding, seeing, and collecting and will serve anyone from a teenager to an adult entering the field.

— Dr David M. Jones, OUGS Proceeding Editor

Book review



Meyer, Jürg 2021 *Rocks and Rock Formatioms: a Key to Identification* (trs. by Mark Epstein) Princeton University Press (ISBN 978-0-69119-952-8, eISBN 978-0-69121-755-0; 192pp; card-cover £16.99)

Originally published in German as *Gesteine enface bestimmen* (2017, Haupt, Berne), this book is an addition to the 'Princeton Field Guides' series.

Meyer provides an excellent, short, visual guide to rock identification as hand specimens and in formations. It is organised into three parts: 'The Fundamentals', 'Identification Key' and 'An Introduction to Rock Classification', each consisting of several chapters.

'The Fundamentals' gives an overview of 'rocks', then describes mineral formation, texture and structure, fossils, weathering and alteration of rocks; and then brief sections on what equipment is needed in the field, excellent advice on a step-by-step procedure in 'Approaching Rocks Intelligently', and some other research methods that can be used in a lab for rock identification.

The text is brief, but thorough. And it is lavishly enhanced throughout its pages with colour illustrations, keys and examples. The print and production are excellent, on a robust, quality paper stock that should stand up to use in the field.

The bulk of the book, pages 57 to 171, is the 'Identification Key'. Through it Meyer provides a methodical approach and colour-key grouping of rocks, with 382 colour illustrations, each captioned with details to help narrow down and identify a rock specimen by following the steps Meyer describes. The illustrations are small, but clear, and will provide an excellent visual aid to identification — after all, the book's format is designed for portability in the field, and you are looking at specimens through your hand lens, so can look at the colour illustrations though your lens as well!

Part III, 'An Introduction to Rock Classification', is brief, but again filled with an amazing wealth of information, mostly in colour charts, diagrams and box tables. It is traditionally organised as 'Igneous' (plutonic and volcanic), 'Sedimentary' and 'Metamorphic'. There are rectangular and triangular diagrams of rock formation, names, temperature formations, grain sizes and other such details, ending with a four-page, colour-coded table of 'Source rocks and their metamorphic products'.The book end with a six-page Index.

Having taken a new look at some of the rocks in 'my collection', I find this book a most useful guide in comparison to some other 'field identification' books I already have. Although the price is £16.99 for what appears to be a 'small' book, the quality and usefulness of this book justifies the cost in my opinion. I would not be surprised to see it on the shelves of many of our OUGS UK and European colleagues (perhaps in its German edition).

— Dr David M. Jones, OUGS Proceedings Editor

A palaeontological tour of south-east Morocco

Kath Addison-Scott

In April 2018 the Geologists' Association organised a field trip to Morocco, led by Professor Dave Martill and Mohammed Segaoui. This article summarises some of the highlights of route from Marrakesh, over the High Atlas Mountains to Ouarzazate, and then over the Anti-Atlas Mountains to Alnif, Rissani and Merzouga (Fig. 1).

High Atlas Mountains

Our trip through the High Atlas Mountains involved driving up and over the Tizi-n-Tichka pass at a height of 2260 m (7415 ft). This Moroccan mountain pass links Marrakesh to the city of Ouarzazate, and is a gateway to the Sahara Desert. From the Col of Tichka we had a good view of the Continental Red Beds. These sedimentary rocks were deposited in Triassic to Lower Jurassic times during rifting of the North American and African plates (Fig. 2).

We then descended into the great valley between the Atlas and Anti-Atlas mountain ranges towards Ouarzazate. The escarpment on either side of the road consisted of Jurassic and Cretaceous limestones, interspersed with some Middle Jurassic basalt lava flows. Red palaeosols can be seen between individual lava flows.

Figure 2 The Continental Red Beds in the High Atlas Mountains, seen from the Col of Tichka.

Stromatolites in the Anti Atlas Mountains

From Ouarzazate we continued our journey into the Anti Atlas Mountains and arrived at Ait-Saoun, which is located *c.* 35 km (as the crow flies) south-east of Ouarzazate on the road to Alnif. Here we viewed a large area of Late Precambrian stromatolites. These grew at the shallow edges of linear and sub-circular ponds that had developed in a shallow depression *c.* 1 km across, and were fed by underground freshwater sources on arid plains (Fig. 3).

Stromatolites are finely layered, bulbous deposits of calcium carbonate built by colonies of cyanobacteria. They were an abundant life form two to three billion years ago, but now are quite rare. The ideal present-day conditions for stromatolite formation are warm, shallow, high-salinity seawater with restricted circulation, under which they grow less than a millimetre a day.

Figure 1 Map of Morocco, showing its border with Algeria. Our trip started in Marrakesh and during the first few days we drove east over the High Atlas and Anti-Atlas Mountains as far as Merzouga — 378 km (235 miles) as the crow flies.

Figure 3 Late Precambrian (Ediacaran) stromatolite at Ait-Saoun (coin diameter 30 mm).

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Figure 4 Late Precambrian (Ediacaran) stromatolites at Ait-Saoun, on the Ouarzazate to Tansikht road (coin diameter 30 mm).

Figure 4 shows a stromatolite-rich layer that formed in a shallow sea in Morocco some 600 million years ago and then was buried by volcanic and volcaniclastic deposits. The stromatolites were later exposed through uplift and erosion of the Anti-Atlas Mountains; their remarkable preservation is due to the present-day arid climate.

Continuing eastwards towards Alnif, we crossed the Anti-Atlas Mountains via the Tizi-n-Tiniffift mountain pass at an elevation of 1660 m (5446 ft) above sea level.

Trilobites at Alnif

Alnif is a centre for trilobite preparation and sale, and is an excellent place to buy a perfect example of the many species and specimens on offer (Figs 5 and 6). Highly skilled craftsmen spend many hours preparing the fossils before selling them all over the world (Figs 7 and 8). Prices were very reasonable in the shops when compared with the prices of the same specimens for sale in the UK.

Figure 7 Fossil preparation table in Mertou's shop at Alnif, with a trilobite on the right.

Figure 5 Sign outside Brahim's trilobite shop in Alnif, with trilobite parts written in French.

Figure 6 Brahim's trilobite shop in Alnif.

Figure 8 Large assemblage of trilobite fossils being prepared in Mertou's shop at Alnif.

Figure 9 Flat Precambrian / Early Cambrian basement rock in the foreground, at Tizi-n-Ferkla. The hill in the background is of Cambrian age and a trilobite site.

We visited two collecting localities near Alnif to examine the strata where trilobites have been found.

The first one was Tizi-n-Ferkla, a site for trilobites of Cambrian age north of Alnif, near Tizi-n-Boujou (Fig. 9). The miners lived on a flat area of basement rock and mined in the nearby Cambrian hills (Fig. 10). One of the miners we met showed us a spectacularly large trilobite that he had found (Fig. 11).

Figure 10 Fossil-miners at Tizi-n-Ferkla lived in small huts on the basement rock.

Figure 11 Giant Cambrian trilobite (Paradoxides) *of Cambrian age, found at Tizi-n-Ferkla and shown to us by the miner who found it (finger-tip at centre left for scale).*

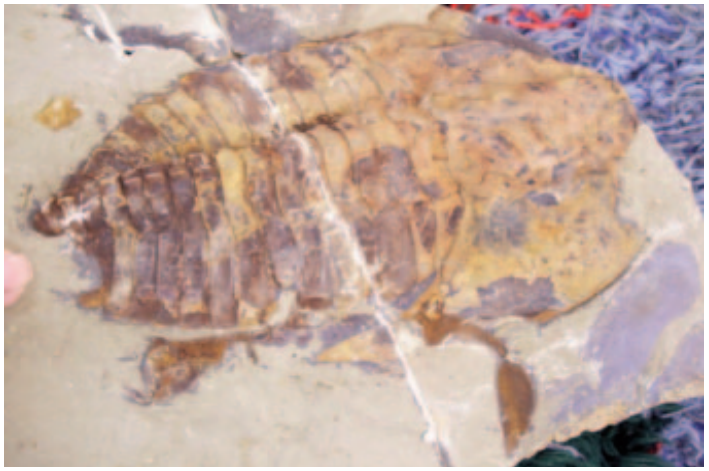


Figure 12 Jebel Issoumour Trilobite outcrop. The green band visible towards the top of the cuesta is spoil from the workings of the trilobite diggings.

The second site we visited was to the south of Alnif at Jebel Issoumour, which is a large cuesta (asymmetric landform with steep scarp slope and shallower back slope) forming the north-western rim of the Mader basin. This area is famous for its Devonian trilobites. Various rock formations from this period are accessible, and many layers have been commercially excavated for trilobites. Local collectors have quarried almost the entire outcrop, now mostly worked out; nevertheless, we spent a couple of hours hunting for fossils and found partial specimens of trilobites, brachiopods, corals and orthocones (Figs 12 and 13).

While we were at Jebel Issoumour we spotted a Berber family making its way across the arid landscape (Fig. 14, *overleaf*).

Oulad-Saidane

Continuing our journey eastwards, we stopped a few miles before reaching Rissani to investigate a ridge of Devonian limestone at Oulad-Saidane (Fig. 15, *overleaf*). This area was full of goniatites and orthocones of *Orthoceras sp.*, as shown in Figures 16 and 17, *(overleaf)*.

Figure 13 Trilobite digging trench at Jebel Issoumour, where we tried our luck and found some fossil parts.

Figure 14 A Berber family on the move at Jbel Issoumour.

Figure 15 Goniatite and orthocone (Orthoceras sp.) *beds in Devonian limestone ridge at Oulad-Saidane.*

Rissani

Next, we stopped at the large town of Rissani as we travelled eastwards towards Merzouga, and visited a preparation factory for the local stone (Figs 18 and 19).

Figure 16 Orthocone (Orthoceras sp.) *in Devonian limestone at Oulad-Saidane (shiny coin diameter 30 mm).*

Figure 18 (right, above) Stone preparation factory in Rissani. Water has been splashed over slabs to reveal Devonian ammonoids and orthocones. The stone slabs can be used for making tables.

Figure 19 (right, below) Shop at the stone preparation factory in Rissani, showing aligned Silurian orthocones (Orthoceras sp.).

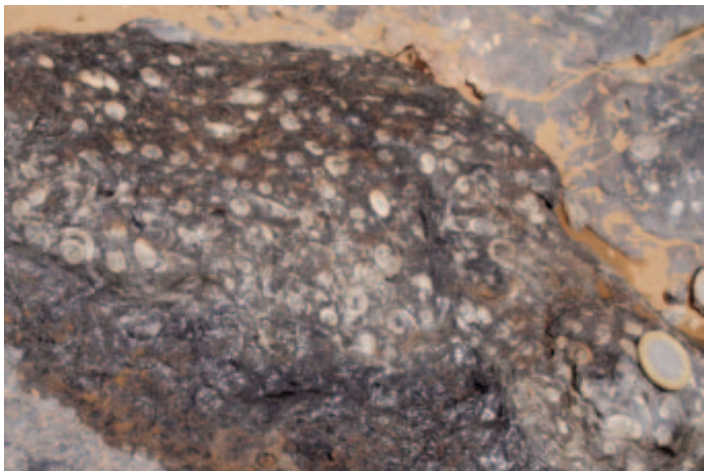


Figure 17 A splash of water highlights an assemblage of Devonian goniatites, cephalopods of the sub-class Ammonoidea, at Oulad-Saidane (coin diameter 30 mm).

Figure 20 Early morning in Merzouga, with large sand dunes of Erg Chebbi in the distance.

Merzouga

Merzouga is a small town situated on the western edge of Erg Chebbi, one of several large 'seas' of dunes formed by wind-driven sand (Figs 20, 21 and 22).

Figure 21 Large sand dunes at Erg Chebbi, with barely visible people and tyre tracks on the upper dune.

Figure 22 Sand dunes at Erg Chebbi, with camel-riders in the middle distance.

Kem Kem Beds

From Merzouga we drove south towards Taouz to investigate the Early Cretaceous Kem Kem beds and to visit the fossil mines there (Figs 23 and 24).

Fossils are mined commercially here and sold around the world. Within these beds can be found fossil vertebrate assemblages of mostly isolated parts belonging to cartilaginous and bony fishes, turtles, crocodyliforms, pterosaurs and dinosaurs, as well as invertebrate, plant and trace fossils. The vast majority of fossils in the Kem Kem beds were deposited in a deltaic environment. Figure 25 shows some of the fossils that were being sold by the local miners.

Our journey through Morocco continued for a few more days and we visited many other interesting places, but that is a story for another time.

Acknowledgement

Base map for Fig. 1: Eric Gaba, https://commons.wikimedia.org/wiki/File:Morocco_relief_location_map.jpg

(An earlier version of this article was originally published in the Severnside Branch Newsletter Sabrina Times May 2021 — Editor.)

Figure 23 Walking up to some workings within the Kem Kem Beds. The pinkish horizon near the top is spoil from the fossil mines.

Figure 24 Fossil mine in the Kem Kem beds.

Figure 25 Miners selling their wares from the Cretaceous Kem Kem Beds. Blue encircles a rostral tooth of the extinct sawfish Onchopristis numidus*, and orange encircles a tooth from the carnivorous dinosaur* Carcharodontosaurus sp.

Cyprus copper: processes of ore formation and metal production — ancient and modern

Duncan Woodcock

Introduction

This article is about processes: the processes that formed the copper ores that sourced the metal and the processes used to extract the metal from the ore. I find both areas fascinating because I am an ongoing student of earth processes and I spent my entire career as a process engineer.

Cyprus is probably best known to earth scientists for its superb and accessible exposures of an ophiolite — a segment of the Earth's oceanic crust, together with the underlying upper mantle, that has been upthrust and exposed above sea level. The Cyprus ophiolite hosts several copper deposits that provided wealth and fame to the island in the ancient world and continue to contribute to the economy of Cyprus today. Four millennia of copper production on Cyprus have left a legacy of slag heaps that were once used for road surfacing but are now protected by law (Fig. 1).

The following section reviews the ore-forming processes. In the final two sections I review the copper extraction processes used up to the end of Roman times, when copper production declined dramatically, followed by its redevelopment in the early-mid-20th century and its recent resurgence employing modern hydrometallurgical methods.

Figure 1 A slag heap in a F922 road cut near Mitsero, c. *25 km south of the capital, Lefkosia. These Roman slag heaps are now protected ancient monuments.*

Ore-forming processes

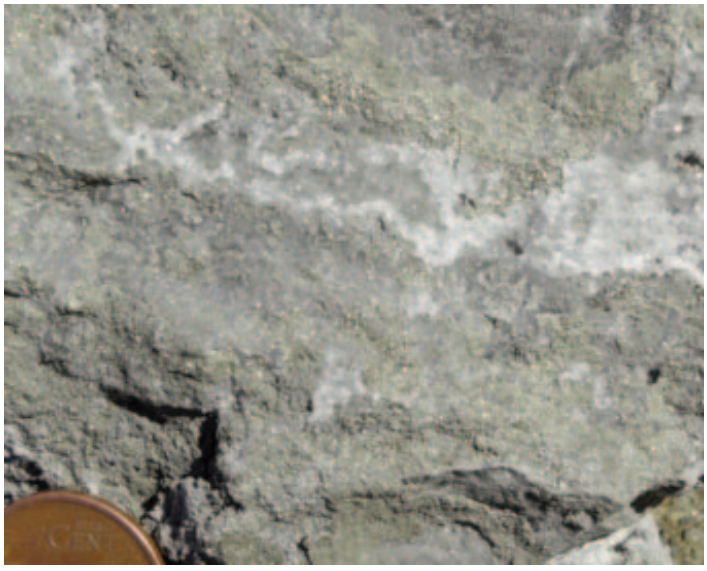
The type of copper deposit within the ophiolite is known as a Cyprus-type volcanogenic massive sulphide (VMS) deposit (Robb 2005). Much of the deposit comprises a massive sulphide body that is typically hundreds of metres in length, tens of metres thick and contains 1–10 million tonnes of ore. The ore is principally pyrite (FeS2) with copper sulphides present as a minor component. The massive body is typically fine-grained, but may coarsen locally to develop large, brassy yellow crystals (Fig. 2). The massive body is underlain by a stockwork deposit in which veins of pyrite and quartz fill fractures within altered basalt (Fig. 3).

Figure 2 Coarsely crystalline pyrite from a massive pyrite body, displayed at the Geopark centre at Pano Amiandos (diameter of coin 20 mm).

Almost all of the copper deposits in Cyprus are hosted within pillow lavas, suggesting that they developed near to or at the surface of the ocean floor. Furthermore, some deposits contain pyritised fossils of species similar to those found around modern hot hydrothermal vents and structures within the massive ore bodies that resemble the chimneys of black smokers adjacent to mid-ocean ridges (Edwards *et al.* 2010). Such evidence is consistent with the formation of Cyprus-type VMS deposits around hot hydrothermal vents adjacent to an oceanic spreading axis.

Figure 4 *(overleaf)* is a diagram of a hot hydrothermal vent, either at a mid-ocean ridge or a back arc spreading axis. Heat energy from the shallow asthenosphere, or possibly an underlying magma chamber, drives aqueous fluid convection within the cooling basaltic crust adjacent to the spreading axis. A diffuse flow of cold, alkaline, sulphate-rich seawater enters cracks and fissures in the surface of the cooling crust. The descending sea

Figure 3 Fine-grained pyrite and quartz in an area of stockwork exposed at the disused Mathiathi open pit mine.



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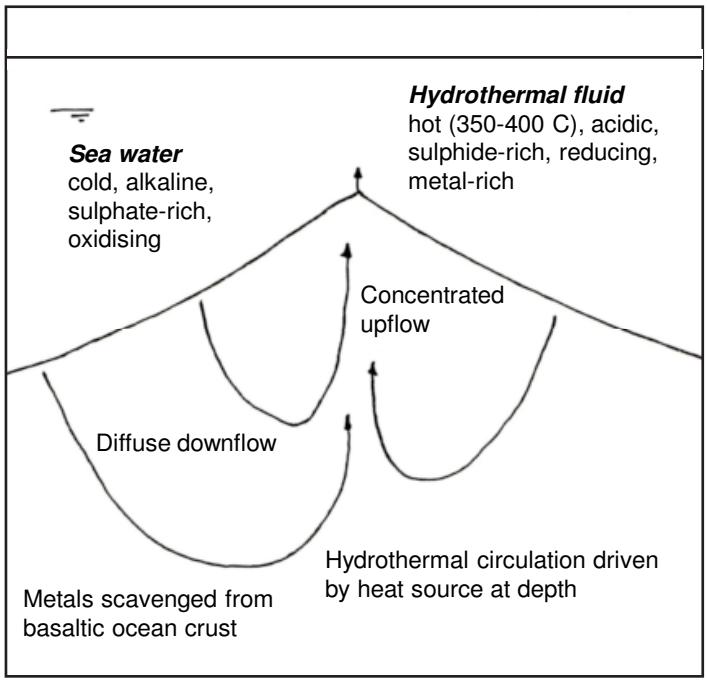


Figure 4 The hydrothermal circulation driven by a shallow heat source at ocean-spreading axes concentrates metals such as copper, zinc and gold in Cyprus-type VMS deposits.

water is heated and scavenges metallic elements from the oceanic crust. Additional reactions of this hot seawater with the crust reduce sulphate to sulphide. The upflow of the convective circulation is focussed above the heat source and comprises a hydrothermal fluid at 350–400°C that is acidic, reducing and rich in both metal and sulphide ions. These fluids discharge onto the ocean floor where they mix with cold seawater. Under these conditions the contrast in chemical conditions promotes precipitation of metal sulphides as a 'black smoker'. Much of this material accumulates locally as 'chimneys' that subsequently collapse to develop a mound on the sea floor, which is permeated by rising hydrothermal fluid to produce the massive sulphide bodies seen in the deposits.

The stockwork underlying the massive sulphide body represents the upper part of the circulation upflow within the crust, where hydrothermal fluid flowing through fractures has deposited quartz and sulphide minerals. Evidence for the deeper circulation can be seen within the underlying sheeted dyke complex, which contains zones of intense alteration. These epidosites (Edwards *et al.* 2010) consist of quartz and epidote, the latter mineral imparting a characteristic green colour to the alteration zones (Fig. 5).

Emplacement of the mineralised oceanic crust during ophiolite obduction, followed by erosion, exposes the sulphide deposits at the surface. Under these subaerial conditions. microbially-mediated oxidation and hydrolysis of the sulphide minerals occurs. The iron liberated is precipitated locally as a mixture of insoluble ferric oxides and hydroxides on the surface to form a gossan. Such gossans have distinctive bright colours that range from yellow to brown and red; they are thus excellent surface indicators of underlying mineralisation (Fig. 6).

Figure 5 Epidotised dyke within the sheeted dyke complex exposed on the Madari ridge at 34° 57' 14" N, 32° 59' 12" E.

The copper ions liberated remain in solution and percolate downwards, where they may be precipitated as carbonate or oxide minerals. These oxidised copper minerals tend to be brightly coloured (Table A, *opposite*); the green malachite and blue azurite would have been easily seen by prospectors in ancient times. Any copper ions that are not precipitated within this 'oxidising zone' above the water table continue to percolate downwards to react with the primary sulphide mineralisation in a process known as supergene enrichment. This process produces a suite of

Figure 6 Extensive exposure of gossan material, 5–10 m high, at Kokkinovounaros, 34° 59' 38" N, 33° 16' 34" E.

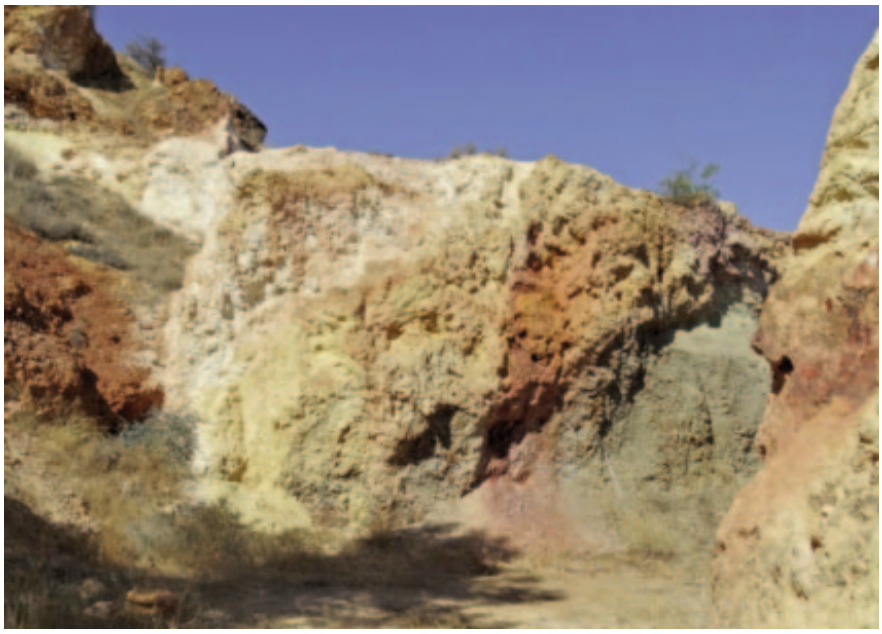


Table A Common ores of copper

Primary minerals		
Chalcopyrite	$CuFeS_2$	brassy yellow
Secondary "oxidised" minerals		
Cuprite	Cu_2O	reddish
Malachite	$CuCO_3.Cu(OH)_2$	bluish green
Azurite	$2\ CuCO_3.Cu(OH)_2$	deep blue
Secondary sulphide minerals		
Bornite	Cu_5FeS_4	copper-red, bronze
Covellite	CuS	blue, purple
Chalcocite	Cu_2S	lead grey

secondary sulphide minerals with enhanced proportions of copper. The oxidised ores, together with the products of supergene enrichment, are generally easy to extract early on during the development of a new copper mine; together with their higher copper grade they can make an important contribution to the viability of a mine.

Copper production in Cyprus before 500 AD

Copper mining and production began in Cyprus *c*. 3000 BC. A ^{14}C date of 2760 BC was obtained from charcoal associated with ancient slags from copper smelting near Skouriotissa (Xenophontos and Malpas 1987). Copper production continued for about 3500 years, with a peak in production in Roman times, and was essentially over by 500 AD (Constantiniou 1994).

As well as several historical references, this era of copper production has left a legacy in the form of an estimated four million tonnes of slag, with about half of it at Skouriotissa (Edwards *et al*. 2010). This slag was the byproduct from the production of an estimated 200,000 tonnes of copper metal. In addition, galleries and shafts, complete with timber supports, that were uncovered during early modern mining at Skouriotissa provide evidence for extensive underground mines during ancient times. On occasions, entrances to mines and prospects can be seen in road cuts (Fig .7).

The prospectors in antiquity would have been drawn to the bright colours at the surfaces of gossans and probably recovered the colourful oxidised ores from shallow excavations. Furthermore, they may have been intrigued to find native copper in the surface layers of the gossan. This was produced by reduction of copper sulphate solution by resin dripping from the dense pine forests that grew in the area (Fig. 8). Evidence for this reaction is provided by timber, left in ancient underground mines, that became impregnated with copper by soaking in mine water rich in copper sulphate (Constantiniou 1994).

Initially, copper was probably produced from the oxidised ores found at shallow depths within the supergene enrichment zone. Such oxide and carbonate ores could be reduced directly to metal at relatively low temperatures by using charcoal as the reducing agent. Once these oxidised ores were exhausted, a process was developed to extract copper from the sulphide ores, probably starting with the richer, more colourful ores produced by supergene enrichment. Treatment of these ores required a preliminary roasting step to remove sulphur as SO_2 and convert the ore to an oxide form.

An additional complication was the need to remove iron by the addition of a flux, which combined with the iron oxide to form a liquid slag phase that was immiscible with molten copper.

Figure 7 This Roman adit in a road cut on the E616 west of Mandria is one metre long on the slant.

Figure 8 Resin dripping from a pine tree, Atalanti Trail, Mount Olympus. Reduction of copper sulphate solution to metallic copper by pine resin is probably responsible for the native copper found in gossans.

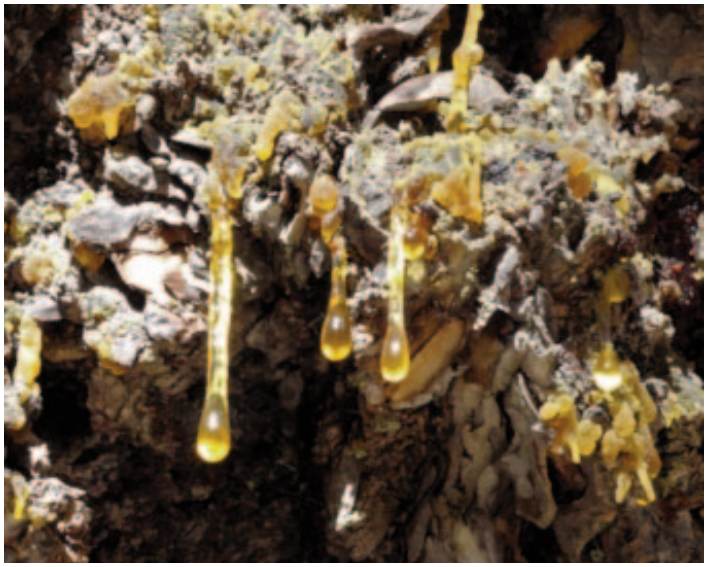


Figure 9 Roman slag on the slag heap opposite the camp of the Argentinian UN peacekeeping force at Skouriotissa, which lies adjacent to the edge of Turkish-occupied territory (diameter of coin, bottom right, 20 mm).

When smelting was completed, the liquid slag could then be poured off and disposed of, leaving metallic copper. Studies of the slags produced show that considerable development of the process took place as various materials were used as fluxes. The earliest flux used was umber, a fine-grained brown metalliferous sediment associated with the ore deposits. Umber flux produced an earthy, reddish-brown slag, in contrast to the later Roman slags, which were generally black and glassy (Tylecote 2002). The Roman slags (Fig. 9) show a reduction in residual copper from around 2.5% in the earliest slags to 0.3% in the later slags (Edwards *et al.* 2010). This process improvement is probably attributable to the use of fluxes that produced molten slag of lower viscosity, thus producing a better separation of the lighter slag phase from the denser liquid copper phase during smelting.

The pyrometallurgical process of roasting and smelting used by the ancients to produce copper required the production of large amounts of charcoal. Metallurgists estimate that *c.* 30 kg of charcoal was needed to roast and smelt the ore to produce 1 kg of refined copper. This charcoal was produced from pine wood (Fig. 10), with *c.* 20 kg of wood required per kg of charcoal (Constantiniou 1994). Taken together, the total production of 200,000 tonnes of copper would have required the harvesting of *c.* 120 million tonnes of wood over the era of ancient copper production.

Figure 10 A large Black Pine tree (Pinus nigra)*, Atalanti Trail, Mount Olympus. Pine trees similar to this one sustained ancient copper production for 3500 years.*

During a recent visit, I surveyed an area of mature pine forest in the Troodos Mountains and estimated a standing crop of *c.* 300 tonne/hectare; thus, an area of mature forest of 4000 km^2 would need to be felled to support ancient copper production. The land area of Cyprus is 9400 km^2, with *c.* 10% currently covered in mature forest, suggesting that the ancient pinewood forests must have been felled and regrown about four times.

A further calculation demonstrates that exploitation of the pine forests was probably sustainable, even in Roman times, when production was at its peak. The area of forest that I surveyed was said to be about 150 years old, which was confirmed by counting tree rings on the occasional stumps of a few recently felled trees. The resulting production rate is thus 2 tonnes/year per hectare, similar to values obtained by Eker *et al.* (2017) for the growth of *Pinus brutia* in Turkish forests. Assuming that all the 'ancient' copper was produced over a period of 400 years ,the annual wood demand would have been *c.* 300 000 tonnes/yr. The corresponding area of forest is 1500 km^2, *c.* 15% of the land area of Cyprus. If the forested area was 50% more extensive in Roman times, timber production to support copper production was probably sustainable on a year-on-year basis.

In the ancient world, several other areas around the Mediterranean, such as Syria and Oman, produced some copper as well, but production petered out through lack of wood. In contrast, copper production in Cyprus was sustained for a period of 3500 years, principally because regrowth of dense pine forests was promoted by heavy precipitation in and around the Troodos Mountains, that were uplifted to more than a thousand metres above sea level by emplacement of the ophiolite (Constantiniou 1994).

Modern copper production in Cyprus

There is no evidence for significant copper mining in Cyprus from *c.* 500 AD until the early part of the 20th century (Constantiniou 1994). Mining restarted in 1921 at Skouriotissa, and in 1929 a large open-pit mine at Mavrovouni began to exploit a large ore body containing some 16 million tonnes of ore with an average grade of 4.5% copper. In the following years, several other open-pit mines were developed, often on the site of ancient underground workings, such as at Mathiothi. The more recent developments tended to exploit lower-grade ore bodies, which together with competition from giant porphyry copper mines in Chile, led to a progressive decline and was essentially complete by the1980s. During this second era of copper production the ore produced was processed by froth flotation (Fig. 11, *opposite*) and the resulting sulphide concentrates were exported for smelting. In addition, some pyrite was mined and exported for sulphuric acid production; from 1950 to 1970, Cyprus was the third-largest pyrite producer in the world. The operations during this era left a legacy of large open pits (Fig. 12, *opposite*), spoil heaps (Fig. 13, *opposite*) and tailings dams.

The current era of copper production restarted around 1996 at Skouriotissa, when the Hellenic Mining Company began to operate a hydrometallurgical process to recover copper from

Figure 11 Remains of a Hellenic Mining ore dressing plant north of Mitsero, which produced sulphide concentrates for export until abandoned in the 1980s.

low-grade ore. This process involves leaching of heaps of ore, collection and treatment of the resulting solution by solvent extraction, and recovery of copper as cathodes by electrolysis (Fig. 14, *overleaf*). This process is much less energy-intensive than a modern version of the smelting process and has the additional advantages of lower environmental impact and production of a product with a purity in excess of 99.999% (Worldfolio 2016).

Summary and conclusions

There were three eras of exploitation of Cypriot copper resources. The first era, from *c.* 3000 BC until 500 AD, used an energy-intensive pyrometallurgical process that relied on regrowth of the Troodos pine forests to sustain it. After a period of quiescence, a second era began in the 1920s to produce sulphide concentrates and co-product pyrite for export, but production petered out in the face of decreasing ore grade and competition. The third era was enabled by the development of a hydrometallurgical process that enabled economic processing of low-grade ores. This last process continues to be operated at Skouroitissa to produce a high-value product that maximises added value to the remaining copper resources.

References

Constantiniou, G. 1994 'A History of Copper Mining'. *Appendix 1 in the OUGS Presidential field trip to Cyprus, 2–12 March 1994*

Edwards, S., Hudson-Edwards, K., Cann, J., Malpas, J., and Xenophontos, C. 2010 *Cyprus*. Harpenden: Terra Publishing

Eker, M., Spinelli, R., and Gürlevik, N. 2017 'Recovering energy biomass from sustainable forestry using local labor resources'. *J Cleaner Production* **157**, 57–64

Robb, L. 2005 I*ntroduction to Ore-forming Processes*. Oxford: Blackwell Publishing

Figure 12 The flooded open pit mine at Mathiathi.

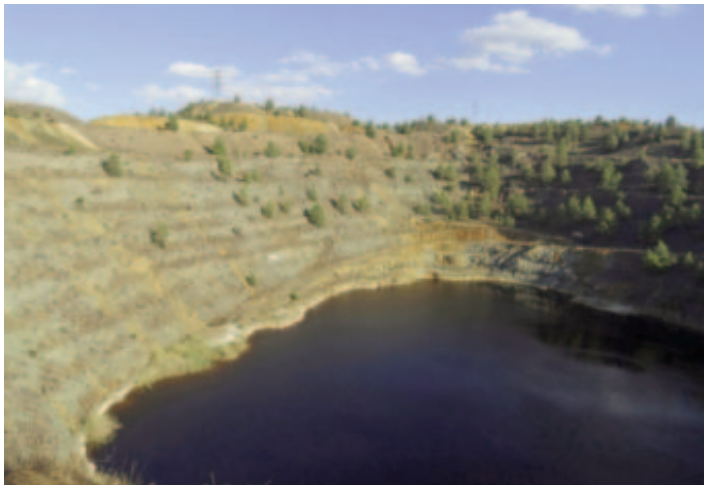


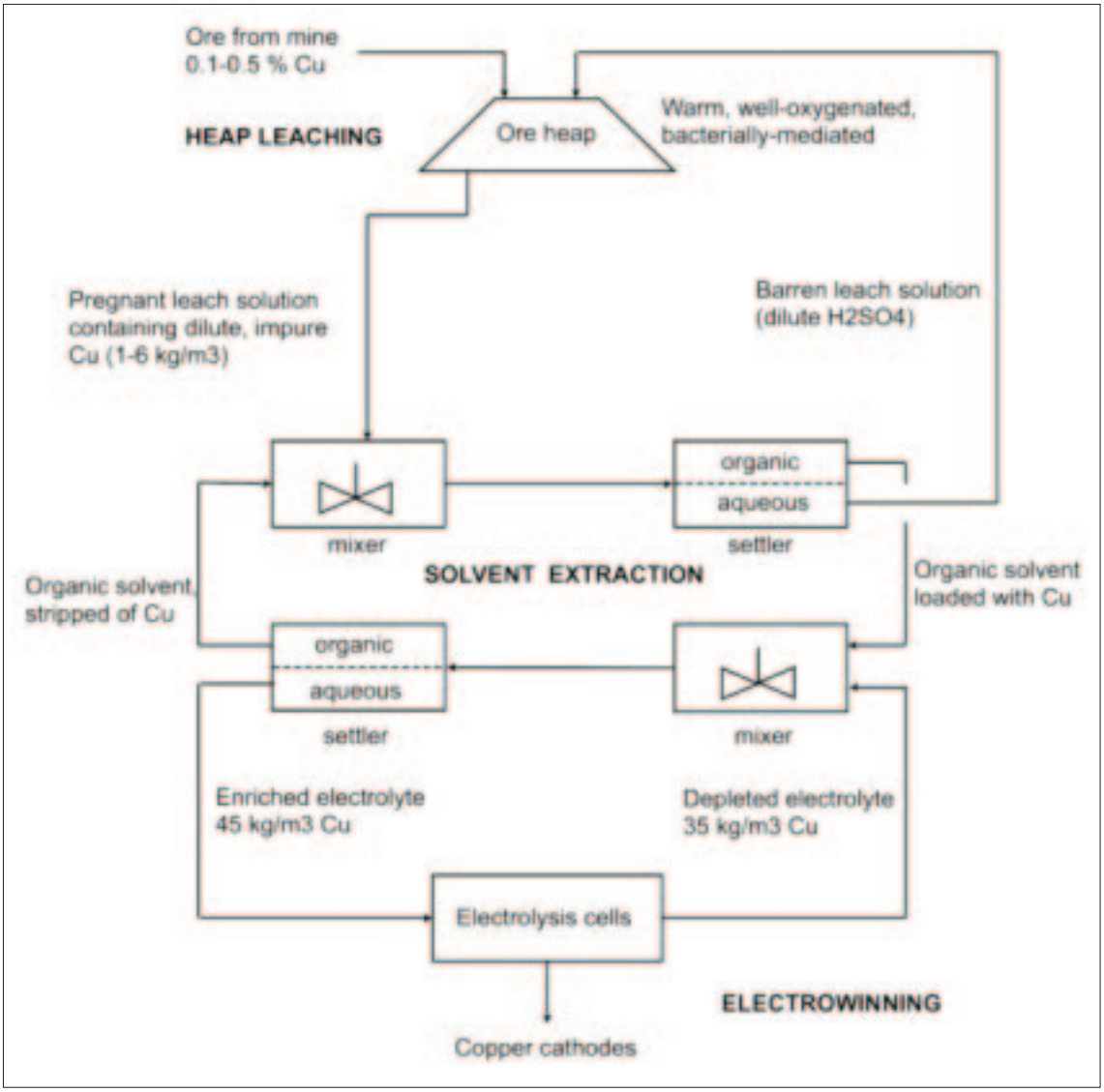
Figure 13 Spoil tips at Kampia mine.

Tylecote, R. F. 2002 *A History of Metallurgy.* London: Maney Publishing

Worldfolio 2016 'World's longest continuously producing copper mine with over 4,000 years of history': http://www.theworldfolio.com/interviews/worlds-longest-continuously-producing-copper-mine-with-over-4000-years-of-history/3799/ (accessed 12-03-2021)

Xenophontos, C., and Malpas, J. 1987 'Excursion C'. *Field Excursion Guidebook: Symposium TROODOS 87, Ophiolites and Oceanic*

Figure 14 Simplified flowsheet for the process used by the Hellenic Mining Company at Skouriotissa to recover copper from low grade ores.



Exploration geology in Western Australia and in the Canadian Yukon

Gosia Musur

Introduction

Some of you may know me from several OUGS field trips I attended between 2013 and 2017. I started on the Earth Science pathway, but as the course was undergoing curriculum changes, I switched to an Open Degree because that way I could complete more geology and maths modules. I had not thought much about what kind of geological work I could get into in the future because, at the time, it all seemed so out of reach. I enjoyed learning about rocks and earth processes, but I could not picture what working in this industry would really look like if you did not go into academia.

A 'working' holiday

In mid-2018, I moved to Australia on a working holiday visa, fully expecting to work in a bar or in a café. Instead, I decided to give geology a go and contacted several recruitment agencies, as I knew there were many mines and potential jobs in Western Australia. Ore mineral exploration was not on my radar yet, but within a few weeks I found myself thrown into the world of exploration geology, which I did not even know existed. After six months, I moved to Canada for two years and continued my adventures as a geologist, working on five different projects in the Yukon Territory.

During the lockdown and restricted periods of the COVID pandemic I know that it must have been sad and discouraging not to be able to go out and explore with the OUGS on field trips, so I would like to share my adventures with you and what I have learned about exploration geology over the past two and a half years.

In general terms, exploration geology is the first phase of mining, with many junior companies acquiring land and looking for deposits of ore, industrial raw materials, solid fuels and gemstones that are big and economic enough to be sold to larger companies for mining rights. Some established mining companies or groups often have their own exploration departments, usually focused on growth and expansion. My ore mineral exploration experience ranges from working for a junior company that just listed on the stock exchange, to deep-hole exploration within an open-pit mine (Fig. 1). Statistically, the numbers are not encouraging, with only one in a thousand projects reaching the mining stage (Gandhi and Sarkar 2016). It is also worth mentioning that these projects take many years to complete, require large sums of money and present a remarkably high risk of failure. Some of the successful projects provide return on investment on 10- to 30-years timescales.

However, for many field geologists, working in exploration is the dream job. Leaving economic geology behind, I would like to describe the field activities I was involved with in the world of gold, silver, zinc and lead exploration.

Using a variety of techniques

Geologists and field assistants (or geotechnicians) are involved in gathering data on the ground using a variety of techniques.

Some of the cheapest prospecting techniques involve mapping, followed by soil sampling, trenching and then drilling. Which techniques are used depends on many factors, including location, cost and the project geologist's approach. I was involved in using all these techniques, but never all on one project.

Figure 1 Clearing a path for the water line.

Preliminary prospecting starts with mapping the area and rock sample collection for lab analysis. If the results come back promising, then a team of soil samplers is sent out to complete a grid. The targets are usually spaced 50m to100 m apart and the teams typically use soil augers to dig *c*. 300–400 mm deep. In Australia, my partner and I did not have that luxury and we had to work with a huge, heavy pickaxe and a shovel instead. We walked for kilometres at a time, in the over 40˚ C heat of the Australian outback, along a grid, all the while adding 250 g to our backpacks every 50 m. Fun (Fig. 2, *overleaf*).

The next technique, trenching, is not used very often in my experience. While some geologists swear by it, others see it as a waste of time and money. It involves digging out a trench deep enough to reach into the bedrock, usually cutting across known mineralisation, or structure, to sample, map and log. These samples are much heavier than soil samples, as they mostly contain chipped rocks.

This technique is also labour-intensive, as the length of the trench is divided into 2 m sections from which the geologists or field assistants collect a 2–3 kg representative sample, using pickaxes and hammers (Fig. 3, *overleaf*). The trench is then logged and mapped by geologists and data is put into a computer program for modelling and analysis.

The final exploration technique used is drilling. There are different types of drills that provide various level of detail for analysis. I have not come across air-core (AC) drilling in Canada, but it was used in Australia in the first pass exploration programme,

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Figure 2 Soil sampling in the Australian outback.

after soil sampling results were returned. AC drilling uses steel or tungsten blades to break the unconsolidated ground, compressed air being used to suck rock chips up to the surface to be collected as samples and analysed (Fig. 4, *opposite*). This method can only penetrate through unconsolidated ground, so a hole is finished when bedrock is reached.

Reverse circulation (RC) drilling is similar to AC drilling, but the mechanism is pneumatic, with a hammer driving the steel-tungsten drill bit into the ground. This still produces chips, but is able to penetrate deeper into the bedrock. AC and RC drilling provide information on bulk samples, usually 0.5–1.0 m thick.

Diamond drilling is used for more detailed information, such as layering and structures. Diamonds are placed at the end of the hollow drill bit, which means it can cut through almost all types of rock. A solid drilled core is pulled up to the surface, emptied and put into specially made core boxes for geologists to analyse and sample. This happens every 5–10 ft (1.5–3.0 m), which is the typical length of a drilling rod. Driller helpers, who do all the rod pulling, physically have the hardest job in camp.

Figure 3 Tooled up in the trench.

The exploration camp

Before I move on to talk about my responsibilities in camp and at the rig, I would like to quickly introduce you to life in camp, as that is an adventure in itself. Not every exploration project requires specifically built wild camp, especially if there is a town or village near by and a convenient road access to the site. My experience of Australian mine camps is incredibly positive, as they reminded me of staying in a two-star hotel. They had good road access, a mess where food was served, a swimming pool, a bar and TV, and a private shower in every room.

On one occasion, my partner and I spent two weeks in an old trailer in the middle of the Western Australian outback. We have witnessed amazing storms passing through and were occasionally woken up by screaming wild donkeys and camels wandering into the middle of our camp.

In Canada, however, my experience has been completely different. Almost all the projects were so remote that you could only access them by either plane and helicopter, or by big and robust four-wheel-drive trucks. This meant that a daily commute from a nearby town (which could be more than 100 km away) was out of the question. There is a lot of uncertainty regarding start dates and duration of projects, so it is almost impossible to plan ahead. The length of our stay in camp also varied, with some four-week shifts offering four weeks off, while others gave us only five days off for every 28 days worked. Everyone works 10–12 hour shifts a day and, unless you are not in camp, nobody gets time off.

Figure 4 Air-core drilling in action. It's a messy business!

As I worked in the Yukon Territory, the remote locations of the camps were in the most exquisite mountainous regions. We slept either in domes (Fig. 5), which at least provided some sort of privacy by being divided into four small private rooms; or in wooden tents, sharing with up to three other people. There is always a huge generator to provide power, a water tank, a 'dry' — typically a separate tent for the drillers to get changed in and dry their work clothes in, a basic shower room with washing machine and dryer, kitchen and mess (sometimes also used as a social room), and an outhouse or two (Fig. 6). Usually, for a small-scale diamond drilling project with one to three drills, there would be between 15 and 30 people in camp: a cook with kitchen help, a camp manager, camp maintenance crew, two heavy machinery operators (one on nightshift), a helicopter pilot, a senior geologist, other geologists and geotechnicians, some drillers and helpers (half on nightshift), and additional staff as needed. Personally, my favourite part of living in camp was the location and the food.

The cook is almost always on hand — sometimes even delivering freshly made doughnuts to the core shack. Breakfast (which is dinner for the nightshift) is typically served between 6 am and 8 am; and dinner (which is breakfast for the nightshift) is served between 6 pm and 8 pm. If you are lucky enough to be based in camp during the day, you also get some delicious hot lunch and unlimited access to tea and coffee.

At the drill site

As a geologist on a diamond drilling project, I was usually in charge of one drill and my responsibilities were either in the core shack or at the drill site. Once the plan for a hole was established, the project geologist would provide the exact GPS location for the drill collar, target depth, predicted depth of mineralisation (or structure of interest), the azimuth and the angle of drilling. It was my responsibility to sight and stake the drill site, which means placing wooden stakes with bright flagging in three places: one at the proposed collar and the other two at the front and back to provide an overall idea of the azimuth for the drill placement. Once the drill was placed at the site, I would use a compass to check if it was perfectly aligned and communicate any adjustments to the driller, if necessary. Ideally, you do not want to be more than two or three degrees off. Downhole surveys are done every 50 m, so you will know how well you have aligned the drill. It is also crucial that the driller has all the important information about the hole, including its name, azimuth, angle of drilling and the target depth. Throughout the drilling process, I would check-in at the drill site at least once a day to see how they were getting on, unless the drill site was on a side of a steep mountain that was only accessible by helicopter (Fig. 7, *overleaf*). These visits were a great opportunity to learn more about the drilling and to appreciate all the hard work the drillers and helpers do.

Figure 5 Sleeping domes in the Yukon.

Figure 6 A toilet with a view.

Figure 7 Safety first: geared up with all my PPE to check the drill sites!

Usually, the core sections were delivered to the core shack twice a day at shift change, which is around breakfast and dinner time. When they came, we had to pick the boxes up chronologically and place them on core racks in the core shack by hand. These boxes can weigh *c.* 10–20 kg, mostly depending on the kind of rock and minerals that are inside. I assure you, when you are moving a lot of core boxes, massive sulphides like galena are not your friend, but they make everyone happy. At the drill, the driller and helper mark the core boxes and depths after each rod pull. It was not uncommon for the depth blocks to end up in the wrong spot, so it was important to check the lengths of the runs. If that was not corrected, the final depth recorded and charged by the drillers was incorrect.

In the core shack

In the core shack, as geologists (and sometimes with the help of geotechnicians, if employed) we were responsible for describing and sampling the core (Fig. 8). When geotechnicians happened to be geology students, or recent graduates, the roles would often be shared. For me, working in the core shack was always about teamwork. We often gathered around interesting pieces of core for short discussions, to share ideas and occasionally to admire beautiful earthly designs. Once the core was delivered and set up in the shack, we took a variety of geotechnical measurements, such as the number of natural breaks, the lengths of all the individual runs and specific gravity. As a logging geologist, I would use a logging database to describe what I saw, in as much detail as required to determine the lithology, mineralogy, potential geological history, structures and alteration zones. Structures, such as faults, veins and natural breaks were recorded in greater detail when dealing with an oriented core, which is marked so that it can be repositioned on the surface as it was originally aligned in the hole.

If I were to choose my favourite tools, it would be a bottle of hydrochloric acid, a tungsten tip scribe with a magnet, and a good hand-lens with an LCD and UV light. Once all the core was logged and the geotechnical data collected, I would prepare samples for analysis. On a gold exploration project, the whole length of core is sampled, because as little as 0.2 g/t of gold could be economically viable. In contrast, lead-zinc-silver projects usually require only select sampling when the core contains minerals or structures of interest. Once sampling is completed, good-quality photographs are taken and boxes containing samples are moved to the core-cutting shack, where they are cut in half by a designated core cutter. One half is sent away for lab analysis and the other half is put back in the box and stored in the core archive with the rest of the boxes. At the end of the day, I would upload

Figure 8 The core shack. Bring tea!

all the data, including the log, surveys and geotechnical information into a modelling program, for example Leapfrog or ArcGIS, for further analysis.

Conclusion

This is the extent to which I was involved in these projects, but there is so much more that goes on in the background. For example, planning the holes and 3-D modelling as soon as data become available, to analyse the nature of the mineral resource. That is something I would like to be more involved with in the future.

In spring 2021, I moved to Sweden to work as a logging geologist at a lead-zinc-silver mine for the summer. In September, I will start a Master's degree in Geomatics at Lund University to improve my GIS skills. After experiencing all this valuable fieldwork, I decided to go back to university, as I felt I have not had enough exposure to modelling programs in the last two and a half years.

Working in exploration geology showed me how the knowledge we gain at university can be used in practice. It also showed me that many of the skills you need in the field are impossible to learn in the classroom, or from a book. This type of work is a great opportunity to travel around the world and to visit places you would not usually be able to see (Fig. 9). I feel lucky to have had the chance to experience this lifestyle, and I hope that this article offers you a glimpse of what working in exploration geology, at this level, was really like. Please feel free to contact me if you have any questions, or if you would like me to expand on any particular topic.

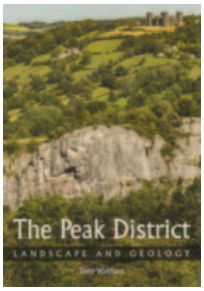
Reference

Gandhi, S. M., and Sarkar, B. C. 2016 *Essentials of Mineral Exploration and Evaluation*. Amsterdam: Elsevier, chapter 7.3

(An earlier version of this article was originally published in the Scotland Branch Newsletter ERRATIx *June 2021 — Editor.)*

Figure 9 Some of the perks of working in the far north: northern lights, big camp fires, and helicopter rides.

Book review



Waltham, Tony 2021 *The Peak District: Landscape and Geology*. Marlborough: The Crownwood Press (ISBN 978-1-78500-874-0; 160pp; paperback £16.99

This is first and foremost a field guide, and it is regrettable therefore that my intention to take it out and literally field test some of the content was unfortunately not possible this past year. This did not ,however, detract in any way from this extremely informative and well presented book.

The book opens with a chronology of what is now the Peak District over geological time ,from Carboniferous times with particular emphasis on the distinction between the 'Dark Peak' region in the north and the 'White Peak' to the south. The divide between these two regions is along a roughly drawn east–west line that passes through Castleton. To the north are primarily rock units derived from seafloor mud, silt, sand and gravels, whereas to the south is a lagoonal reef-derived limestone upland. Copious clear diagrams illustrate the depositional environments, tectonic plate movements and erosional actions that have brought about this regional divide.

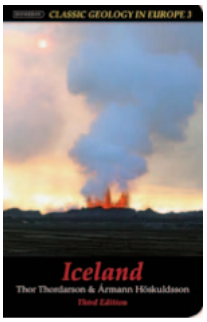
Thereafter the book covers, with several chapters to each section 'Creating the landscape' and the 'Imprint of mankind'. While the creation of the landscape has in a sense been an on-going process over hundreds of millions of years, the present-day visible landscape has been mostly fashioned by erosion process over the past one million years, and the sections explore the discrete outcomes of erosion on the limestone or gritstone exposures. The latter section explores the widespread mining for metal mineral ores that has now ceased, but has left substantial relics, before addressing the on-going mining and quarrying for stone for decorative and construction purposes.

Suggested viewpoints and features are clearly described and while practical geology is by necessity an outdoor activity within the environment as presented, none of the access points appear to require, from my limited knowledge of the area, overly strenuous outings.

The figures and graphical illustrations throughout are clear and readily followed, making this a guide that is suited to most readers who have a modest understanding of basic geological processes and terms. Meanwhile the photographs, largely taken by the author, are not only numerous, but have been taken from view points both panoramic and in close-up that clearly and distinctly depict the features of interest. Taken in conjunction with the more technical Geologists' Association guides this book will be a valuable resource for any field trip.

— Chris Popham, OUGS South West Branch

Book review



Thordarson, Thor, and Höskuldsson, Ármann 2022 *Iceland* (3rd edn)(Classic Geology in Europe series). Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-092-5; 280pp; paperback £25; also available in ebook format)

This is the third edition of this book, first published in 2002, with a 2nd edition in 2014. This edition includes a new section describing the 2014–15 eruption at Holuhraun, and publication was delayed from March 2021 to include a brief addendum on the Fagradalsfjall eruption at the Reykjanes Peninsula.

The first chapter gives a comprehensive and succinct overview of the geology of Iceland in its unique tectonic and hot spot setting on the Mid-Atlantic Ridge. The chapter describes the geological framework of Iceland's volcanic zones and belts, the volcanism and its products, volcanic architecture, as well as the products of glacial activity, sedimentary processes and the stratigraphical succession of 18 million years of geological history.

The following nine chapters are each dedicated to a geographical area of Iceland, starting in Reykjavík and the south-west and moving anti-clockwise around the country, with the final chapter being the central highlands area. The book is intended as a field guide to excursions around Iceland, and describes more than 50 localities, which provide examples of all the diverse geological processes and their products. Localities are marked on a geological map of each region and directions are given on how to get to them. All the places mentioned in the text are given GPS co-ordinates, which are also listed in an end section of the book. I tried being an armchair traveller by virtually using the co-ordinates to visit some of the localities, but this proved a fairly laborious way of getting around and does not nearly compensate for being there on the ground.

The book is lavishly illustrated with colour photographs and illustrations, as well as with maps and graphs, which repay careful study in conjunction with reading the text. I did find it a little difficult to read the legends on the maps, the size of which have been reduced to fit in with the paperback format of the book, so the font was tiny; but I kept my geological map of Iceland to hand, which I was able to consult when necessary.

I liked that many historic volcanic events are described with reference to eye-witness accounts. For example, there is some documentary evidence of the Eldgja eruption in 934–940, a description of the eruption of Hekla in 1300, contemporary accounts of the Laki fires in 1783–84; and more recent events such as the formation of Surtsey in 1963–67, and Eyjafjallajökull in 2010, plus others too numerous to mention.

I saw no mention of a translator and I am totally in awe of the authors who can write so lucidly in what I assume is for them, a foreign language. I enjoyed reading the book and am inspired to get on a plane and go visit these places again, *Classic Geology in Europe: Iceland in hand.*

— Suzanne Grain MSc (Open), BSc Hons (Open), BA Hons (Wales)

The 2010 Eyjafjallajökull ash cloud

Angela Scarrott

Introduction

In mid-April, 2010, there were stirrings beneath the Eyjafjallajökull volcano in Iceland, which then erupted in spectacular fashion, launching huge volumes of volcanic ash high into the atmosphere, to cause utter chaos to airline flight plans across western Europe.

My interest in all things planetary led me to monitor the eruption, the ash cloud, the jet stream and weather movements; as I did so I realised that the ash cloud might well come right over our heads here in Cornwall. I then worked out when it might be overhead.

Sharing a coffee on the patio with a non-geological friend a few days later, I was explaining it to her and put my mug down to make a point with both hands — and stopped!

The table was gritty!

We shot out to my car to find it covered in fine honey-coloured, gritty dust (Fig. 1). I went back into the house for my camera, a brush, sticky tape and specimen bags — had I actually managed to get a specimen?

The next morning, I took the opportunity to take my specimens to work at the Royal Cornwall Museum (RCM) to view them with a microscope and take some photographs. My specimens did indeed look to me as if they contained volcanic glass.

Figure 1 Ash-fall on my recently cleaned car, held in the pattern left by that morning's dew (18/04/2010, 10:13, Truro, Cornwall).

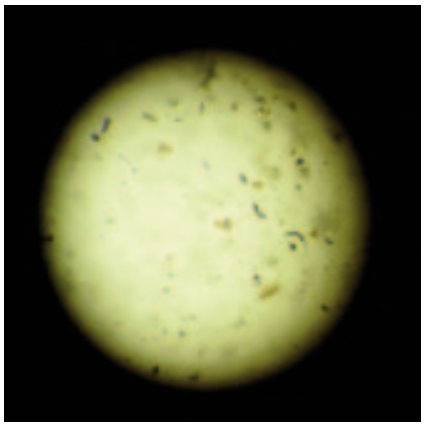


Figure 2 The first view photographed down the microscope: dust collected from the bonnet of my car the previous day. The honey-coloured fragments are the ones of interest, especially those showing conchoidal (glass-type) fracture edges.

The photographs

(Figs 2–9: taken with my digital camera, hand-held to the microscope camera port, at RCM, Truro, 19/04/2010, 09:40–10:25.)

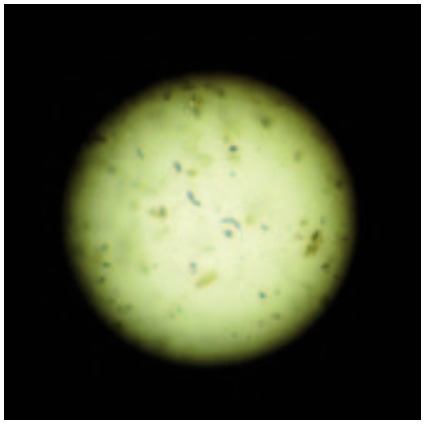


Figure 3 A better-centred photo of the field of view in Figure 2 (width of view unknown). These fragments were visible to the naked eye.

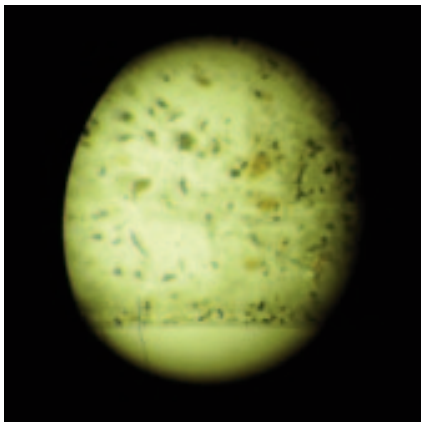


Figure 4 At point of collection, some of the dust was put into a small specimen bag to avoid contamination. This view shows the much greater density of particles, photographed through the bag.

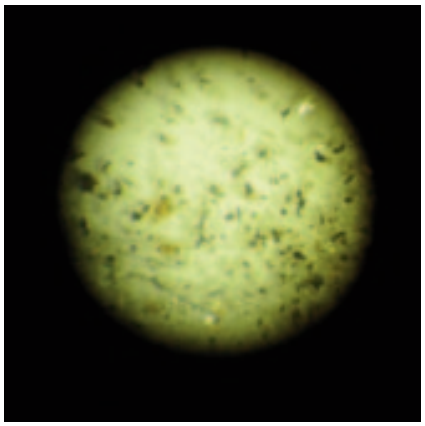


Figure 5 Farther across the same field of view as in Figure 4, to better show the two honey-coloured fragments seen to the left of the 'running man' dust particle (just left of centre).

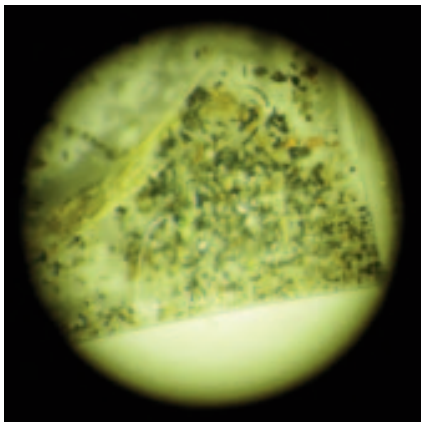


Figure 6 Spotted in the corner of the specimen bag, this interesting translucent honey-coloured cluster, perhaps spun-glass hairs that solidified at the instant of their expulsion from the volcano.

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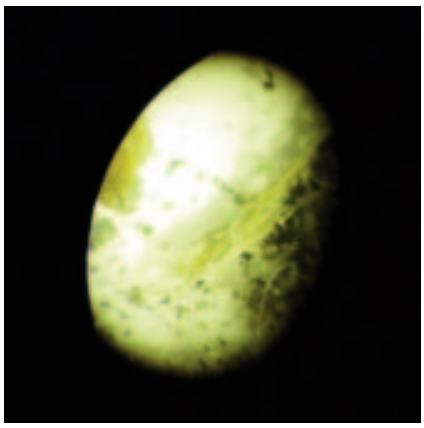

Figure 7 A slightly different view of the glassy cluster seen in Figure 6.

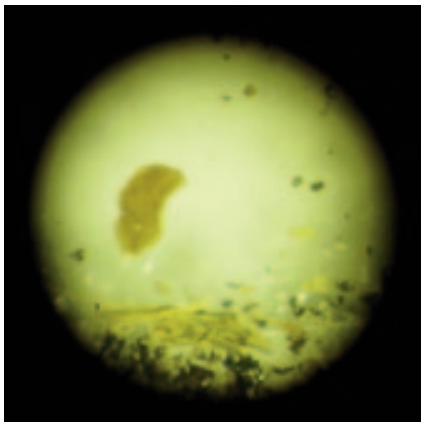

Figure 8 The clearest of the three photos taken of this particular large honey-coloured glassy fragment (fragment length c. *2mm). (This is the photograph shown to Dr David McGarvie at the OUGS AGM — see below).*

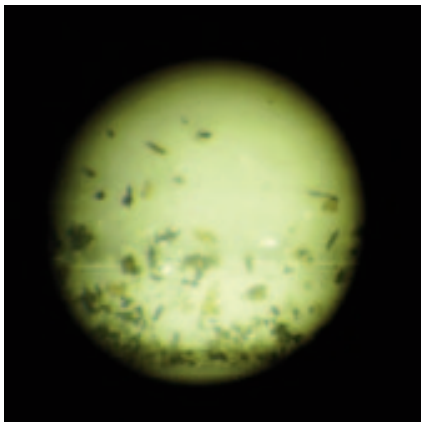

Figure 9 Photograph showing a variety of the honey-coloured fragments.

Finding out

The next national gathering of the OUGS for our AGM later that month brought Dr David McGarvie to deliver the Geoff Brown Memorial Lecture. He came to speak to us about his recent field research on the ice field around Eyjafjallajökull, and showed us the most astonishing video of the actual eruption that cast the ash so high into the atmosphere — wonderful. After Dr McGarvie's lecture, once the crowd around him thinned, I was able to show him my photographs and to ask him what he thought.

I *had* done it! My specimens were of Eyjafjallajökull volcanic ash.

The science

The island of Iceland exists where the additional thermal crustal uplift caused by a mantle hotspot has raised the overlying Mid-Atlantic spreading ridge above sea level. The axis of the ridge itself has been bowed to the east by the complex patterns of uplift and lateral movements of the magmas resulting from both these sources.

Eyjafjallajökull has formed in a region under significant tension (Fig. 10).

Before the 2010 eruption the volcano was covered by a small ice field or ice cap *c.* 200 m thick.

The first effusive phase of the 2010 eruption began late on 20 March, when a tension-relieving NE–SW fissure 150 m long opened on the flank of the volcano, beyond the ice cap. Quite viscous, the effused alkali olivine basalt lava fountained to *c*. 150 m high before flowing slowly away.

On 31 March a similar fissure opened near by and the effusive phase continued, but the ice cap remained undisturbed.

Following intense seismic activity on 13 April, fresh activity began on the 14 April within the summit caldera itself, under the ice cap. Meltwater began to run out, then an eruption column shot high into the air. The explosive second phase of the eruption had begun. A mental image of champagne gas bubbles shooting out of a shaken bottle — all fizzy spray and spilt froth — and of a smashed lightbulb would provide an impression of the effects of such an eruption.

Figure10 Simplified geological map of Iceland and surrounding seas, showing position of Mid-Atlantic Ridge and Eyjafjallajökull (based on Wikipedia image, Creative Commons License).

Once the ice melt got into the active crater, it greatly magnified the violence of the eruption, as the water was instantly vapourised to huge volumes of steam. The whole chaotic mess exploded from the crater, propelled by the pressure of the volume change, added to the eruption of the volcano itself.

Such violent exposure to the air caused instant chilling of the flying magma bubbles, droplets and splatters into volcanic glass. Solidifying far faster than ordinary rock crystals would form, this glass instantly shattered to tiny shards of ash.

The fragment-laden eruption plume rose rapidly through the atmosphere to more than 8 km (5 miles), to be injected straight into the strong Polar Jet Stream passing directly over Iceland at that time (Fig. 11, *opposite*).

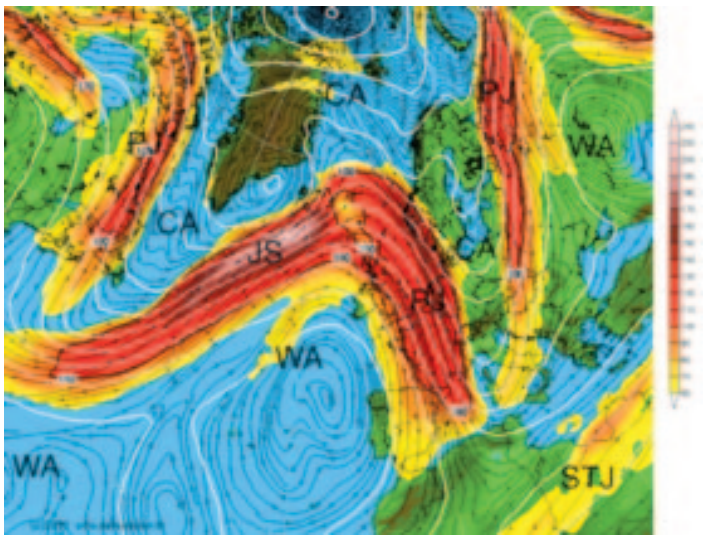

Figure 11 An example of the Polar Jet Stream over Iceland in 2018: the darker the red, the faster the speed of the jet stream (the Polar Jet Stream chart for 14 April 2010 was unavailable; with the kind permission of Netweather.tv).

This plume climbed far higher than is usual for such a relatively small eruption, caused by the extra impetus from the flash-vaporisation of the glacial meltwater.

Airport chaos

Travelling at speeds of more than 100 mph, the Jet Stream carried the erupted, fine fragments of volcanic glass swiftly south-eastward towards mainland Europe where the fragments began to drift down, contaminating the ascent and descent flight-paths of all the airports. Air travel was disrupted throughout western Europe by the descending ash cloud, and flights across Europe were cancelled 'for the duration'.

During the grounding, we learned that the jet engines that move our planes so easily around the planet only function within very fine tolerances, and that flying through clouds of something as tiny as these shattered glass fragments can cause engine failure, with potentially catastrophic consequences.

Figure 12 The spreading path of the ash cloud with the Jet Stream from Iceland to western Europe (© [UK] Met Office).

The details of how a jet engine works are complex, but basically the great blades of jet turbine engines spin at enormous speed, with incredibly fine gaps between the individual blades and between the blades and their housing. Their function is to control the air-flow into the engine. The operating temperature within the engines is *greater than* the melting point of the volcanic glass fragments.

The blades themselves are kept from melting by the cooling air passing through miniscule perforations across their surfaces. These perforations could become filled by the molten glass, which would block the cooling and increase the weight of the blades, thus affecting the stability of the engine, given the high-speed of rotation of the blades.

Over the duration of the explosive phase of the eruption, ash was added to the unusually strong Jet Stream, to gradually fall into the weather systems being drawn along beneath the wake, spreading ash contamination ever farther. For my own interest, I compiled quite a computer record, combining information on the Polar Jet Stream's positions and of surface weather systems with successive daily aviation hazard maps of the risk zone. This information revealed the steady expansion of the ash cloud, moving across and around mainland Europe. Eventually, it became clear that part of it was heading back westwards, towards northern France and southern Britain. I was able to forecast when the leading edge of the ash-laden air mass would come over Cornwall and looked forward to seeing if I could detect any sign of it passing overhead (Fig. 12).

Conclusion

Finding my car covered in fine honey-coloured gritty dust was extraordinary and right on time too! The following day, Truro was blanketed by the strangest haze as the main bulk of the air mass continued to pass slowly over us, as shown in the photograph of the shrouded cathedral (Fig. 13, *overleaf*). Over the next day or so the weather moved on and the air cleared. Western European airspace was finally reopened for commercial flights and aircraft contrails could be seen again in the skies over western Europe (Fig. 14, *overleaf*).

The largest shard of volcanic glass (*see* Fig. 8) in my sample is *c.* 2 mm long; the rest are smaller. How extraordinary that such fragments had been lofted all the way from Iceland. I still marvel at their journey and wonder what the flight profile for those fragments was? How far did they travel in the Polar Jet Stream before sinking into the weather circulation below and what route across the map did they trace on their way back down to Earth, finally to be held in the tracery of overnight dew left on my car in Truro?

A final thought: I wonder if the very ash that Dr McGarvie saw flung into the sky over Iceland contained those particular fragments of glass that were carried aloft to Cornish airspace for me to collect in Truro.

Information sources

https://en.wikipedia.org/wiki/2010_eruptions_of_Eyjafjallaj%C3%B6kull
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2011JD016762

Figure 13 Truro Cathedral seen through the airborne ash haze, photographed from the top floor office in the Royal Cornwall Museum (19/04/2010, 08:01).

Figure 14 Contrails began to be seen as soon as the air cleared and airspace was reopened (1/04/2010, 06:35hrs, from RCM, Truro).

Torquay decorative ‘marble’

Chris Popham

A detailed account of the formation, distribution, quarrying and use of these decorative stones is given by Gordon Walkden in the Geologist’s Association guides, numbers 71 and 72, entitled *Devonshire Marbles: Their Geology, History and Uses*.

The decorative ‘marble’ found in parts of Devon, including Torbay, is not conventional marble resulting from limestone metamorphosis, but rather coral reefs that formed during the Devonian Period *c*. 400 Ma, which have developed an outward appearance of marble. In many cases the basic structure is fossil coral or stromatoporoids, often in life position, where the interstices have been filled with carbonate ‘mud’. The mud frequently contains fragmented storm washed reef materials mixed with the local red sand. Organic deposits may in places have settled on the reefs, which, after decomposition, have left thin dark bands. Calcite precipitation from solution also created a limestone breccia that cemented reef debris and enclosed parts of the reefs.

Fractures, faults, tension gashes and sheer zones in the limestone caused by tectonics may have subsequently filled with additional calcite, which can be white or stained in shades of yellow and orange largely by iron oxides. The layering, deformation of structures, brecciation, and coloured infill has in some cases produced limestones superficially reminiscent of marble.

Surface limestone outcrops occur widely, though sporadically, in South Devon and stone was quarried for general building use, though almost every quarry also operated at least one lime kiln to produce burnt lime either for building applications or as a soil conditioner.[1] Marble was found in some more specific locatities, notably around Plymouth, Newton Abbot and Ashburton. Meanwhile in Torbay there are numerous coastal quarries, some of which produced marble, with perhaps the most highly prized variety coming from the small valley at Petit Tor Beach.

Around Torbay various examples of marble can be seen *in situ*. For example, the upper surface of Triangle Rock at the far end of the beach huts at Meadfoot exhibits mats of coral and stromatoporoids (Fig. 1), though at Shag Rock 300 m off-shore, the same beds are exposed,but have been undercut and are more clearly revealed. Within the sea wall at Meadfoot a variety of marbles can be found, particularly at the slipway near the beach huts (Fig. 2). Many of these blocks show colourful veining, though from the exposed fossils it is apparent that not all are the right way up. Similar blocks can be seen in the sea wall along the promenade at Torre Abbey Beach.

At Long Quarry Point on the north side of Anstey’s Cove, a quarry produced a pale grey limestone in which large solitary corals can be seen. The location is difficult to access, but is nevertheless popular with people fishing and over the years repeated footfall has given some of the stone a high polish. The promenade at the western end of Sidmouth seafront runs beneath the Clock Tower Cliff and in places the cliff has been supported by walls built, I am reasonably convinced, from Long Quarry limestone, in which corals and stromatoporoids are prominently displayed.

Figure 1 A coral mat with stromatoporoids.

Across South Devon many of the roadside kerb stones are limestone. While footfall has often given a modest polish to the upper sides — a finish that is best seen when wet — the roadside-facing kerbs have sometimes been highly polished by contact with car tyles. West Street in Ashburton has numerous examples, possibly from Linhay Quarry near the town (Fig. 3, *overleaf*).

Figure 2 Meadfoot sea wall.

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Figure 3 Polished kerbstone in West Street, Ashburton.

Shaped and finished marble can be seen in public buildings such as Oldway Mansion, Torbay, or in churches, for example All Saints, Babbacombe (Fig. 4). In private homes, Asburton 'Black' marble was favoured for fire surrounds. Such was the appeal that Devon Marble was shipped around the world, often as large pieces, and I am reasonably convinced the four-part columns outside The Crown Liquor Saloon in Belfast are varieties of Devon Marble.[2]

Glassels[3] are found on many Torbay Beaches, and are particularly numerous on Oddicombe Beach. For polishing purposes these were first cut with a diamond blade. Doing so, however, produces a frosted surface as the limestone tends to splinter around the grains or along lines of weakness.The next step therefore uses a diamond-faced stone grinding disc to achieve an even, though scuffed, surface that at least revealed the potential of each piece.

Figure 4 Polished marble font, All Siants, Babacombe.

Figure 5 My drill-stand polishing set-up.

Polishing the stone

A set of polishing discs and a mounting pad for a drill can be bought for a modest price that entirely belies their effectiveness. The pads in my set span the range from a coarse 50-grit to a fine 3000-grit.

For convenience, I used a drill stand with the pads uppermost (Fig. 5), and by first using the coarse 50-grit pad, good results were obtained progressing through only the 150-, 300-, 500-, 1000-, 2000- and 3000-grit pads.

The initial polishing step with the 50-grit pad takes the longest time, as this removes the surface scratches. Some surfaces can, however, require more investment at this stage, as their composition renders them prone to heavier flaking during cutting. Thereafter the surface requires no more than a double pass with each pad, helped by wetting the marble to create a lapping paste on the surface that facilitates the polishing process.

Nevertheless, the indented surface of the polishing pads leaves a slight smearing on the surface, which can be removed simply using a drill-mounted, wetted foam pad and polish intended for car bodywork. Fine cracks or cavities in the marble do fill with compacted stone dust, producing a network of white threads, which can be lessened by high pressure washing with water before final polishing.

Figure 6.

Figure 7.

The finish on the polished surfaces can be somewhat variable, possibly owing to the coarseness and abundance of the sand component. For example, a piece with yellow calcite veins in a red sandy matrix took a polish on only the veins, while the surface of the friable sand remained matt (Fig. 6). At the other end of the spectrum, a piece that is apparently only calcite took the highest polish (Fig. 7).

Perhaps the most rewarding piece began as a pebble about the size of a honeydew melon with a non-descript mottled surface, but turned out to be a through-and-through example of the marble variety known as 'Fossil Petittor', which consists primarily of packed coral fragments in a calcite cement and also exhibits the dark organic decomposition streaking (Fig. 8).

Figure 8 'Fossil Petittor' marble.

Figure 9 Stone 'cairn' Petit Tor Beach.

At Petit Tor Beach (Fig. 9) other beach-goers had piled up some of the loose surface debris into a cairn, exposing many sawn marble pieces ranging from thumb-size up to cut slabs 1 m across (Figs 10 and 11). The range of marble varieties revealed was broader than those expected from Petit Tor Quarry alone; and among the marble there was also a cut piece of black basalt.

Figures 10 and 11: examples of sawn marble stone slabs on Petit Tor Beach.

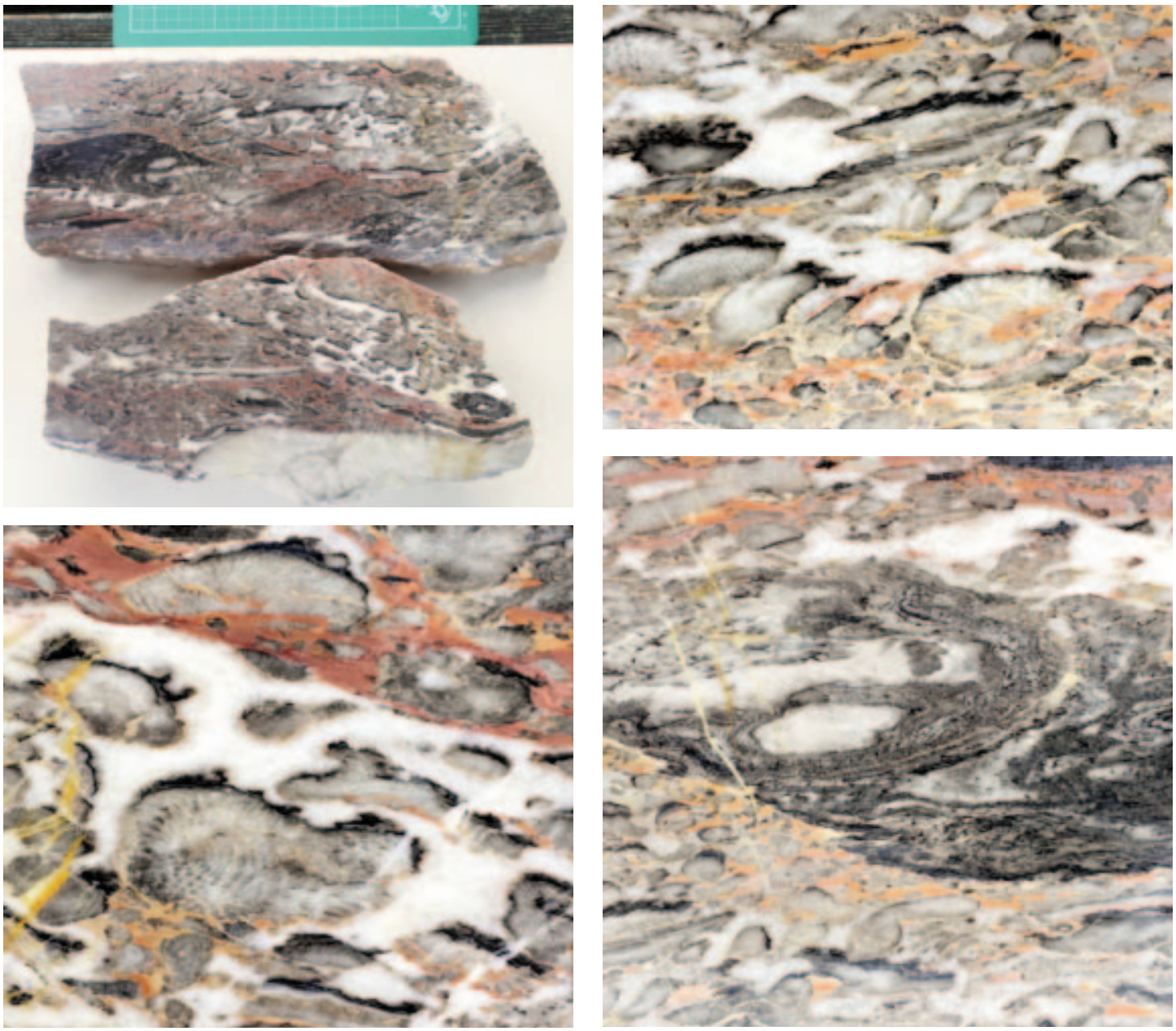


Figure 12 Examples of slabs cut from a 'Fossil Petittor', exposing details of corals (top left), calcite veining (top right), a zone of calcite deposition (bottom left) and a somewhat distorted stromatoporoid (bottom right).

One of the notable uses for the marble was the creation of marquetry inlays for which the a wide variety of form and colour was desired. Consequently, the variety seen on the beach is a result of pieces being brought from elsewhere for cutting and dressing.'Hatched' marks on some of the surfaces suggest that the marble was cut with a band saw rather than with a circular saw, with the intention of producing slices *c.* 20 mm thick.

Unsurprisingly, the Fossil Petittor variety is very common here, including a piece with a cut face measuring *c.* 400 mm × 150 mm. Several slabs were cut from that piece, exposing detail of corals, calcite veining, a zone of calcite deposition and a somewhat distorted stromatoporoid (Fig. 12). Unlike the rigid skeleton of many corals, stomatoporoids grow as flexible mats, which are consequently prone to folding during stormy conditions.

One of the earliest documents to attract my attention to Devon Marble is an extract passed to me by OUGS member Tim Legood (Fig. 13, *opposite*), which suggests that Ipplepen Red Marble was a variety much in demand. The Beltor (latterly Biltor) Quarries worked the ridge to the east of the village and one remains easily accessible, as a road has been laid through it. However, the limestone is primarily calcite 'mud' and shows little marbling. This is a similar situation to the other two quarries along the ridge, both of which are presently privately owned. Of the Barton quarries, one was used as a tip and is now buried beneath tennis and basketball courts, while the other is completely overgrown. At the time of writing, I have contacted the landowner and hope to take a detailed look as soon as possible.

The only other variety I have been able to identify by an established name is Madrepore Marble (Fig. 14, *opposite*), the name derived from the coral variety it contains. While the piece I have was found on the bank of the River Dart near Ashburton, there is a Madrepore Road off Torquay's main shopping street where there were once extensive quarries, and I have been told that quarry workers were sometimes known as 'Madrepore Workers'.[4]

BRITISH AND FOREIGN

MARBLES

AND

OTHER ORNAMENTAL STONES

A DESCRIPTIVE CATALOGUE
OF THE SPECIMENS IN THE
SEDGWICK MUSEUM, CAMBRIDGE

BY

JOHN WATSON
Hon. M.A. (Cantab.)

Cambridge:
at the University Press
1916

red markings. A recent example of the use of this marble may be seen in Cambridge, the new pavement in the interior of Sidney Sussex College Chapel (1912) being largely composed of it.

18*. RED IPPLEPEN.
Barton Quarries, Ipplepen, Devonshire.

A little further south, in Ipplepen itself, a village about midway between Newton Abbot and Totnes, there is an outcrop of Devonian rock which yields one of the handsomest varieties of this group of Devonshire Marbles. As the large slab shews, the red and grey ground-mass is interspersed with light pink veinings. Fossils are hardly recognizable in this example, but what can be seen suggest *Alveolites*.

This marble was much in request in the middle of last century, and many of the ecclesiastical and other buildings in Devonshire, built and restored during that period, were decorated with Red Ipplepen. Good examples of its use as a decorative stone may also be seen in London. There are forty polished monolithic columns made of this marble in the National Provincial Bank, Bishopsgate Street (1866), and two columns of it are in the New Freemasons' Hall (1864).

19. STONEY COOMBE.
Stoney Coombe Quarries, near Ipplepen, Devonshire.
Presented by The Stoney Coombe Stone and Lime Co., Ipplepen.

This specimen is an example of a lighter coloured variety from the same district as the marble last described. The markings shew slight traces of fossils; examples of *Alveolites* are present, although indistinct. Besides making a useful decorative stone when polished, it is also used for ordinary building in Devonshire.

20. LITTLE BELTOR (pink).
Marble Quarries, Ipplepen, Devonshire.
Presented by Messrs H. T. Jenkins & Son, Torquay.

This is a highly crystalline rock and the component organisms have therefore become indefinite. It is known commercially as Little Beltor Marble. There are two varieties, which are distinguished as Pink and Yellow. This specimen represents the former. It is a pink and grey mottled stone with slender red markings.

21. LITTLE BELTOR (yellow).
Marble Quarries, Ipplepen, Devonshire.
Presented by Messrs H. T. Jenkins & Son, Torquay.

This specimen represents the yellow variety of Little Beltor Marble. Yellow, pink, and grey are present in the matrix, and it is intersected with white veins of calcite.

22. SILVERLEIGH.
Marble Quarries, near Buckfastleigh, Devonshire.
Presented by Messrs H. T. Jenkins & Son, Torquay.

A few miles west of Ipplepen, near Buckfastleigh, there are quarries which yield a very dark grey, nearly black, semi-crystalline rock, intersected with numerous white veins, which when polished makes a useful decorative stone. This variety is known commercially as Silverleigh Marble.

23. KINGSTEIGNTON.
Marble Quarries, near Torquay, Devonshire.
Presented by Messrs H. T. Jenkins & Son, Torquay.

The quarry that furnishes this variety of Devonshire Marble is situated about eight miles from Torquay. It is a light pinkish grey rock, through which numerous fossils are scattered, chiefly corals and Stromatoporoids.

Figure 13 Title page and pages describing some Torquay marbles.

Overall the cutting process is noisy and dusty, and the use of cutting blades means there is potential for flying stone fragments. The water spray during polishing is also quite messy. Safety equipment is essential: dust mask, gloves and full face protection. Any limestone paste should be promptly washed from exposed skin as it can be caustic.

Figure 14 Madrepore marble.

As South Devon was not the only part of the country to produce decorative 'marble', if anyone is inclined to repeat the process with local stone the above is not a risk-assessed guide and your health and safety is entirely your responsibility.

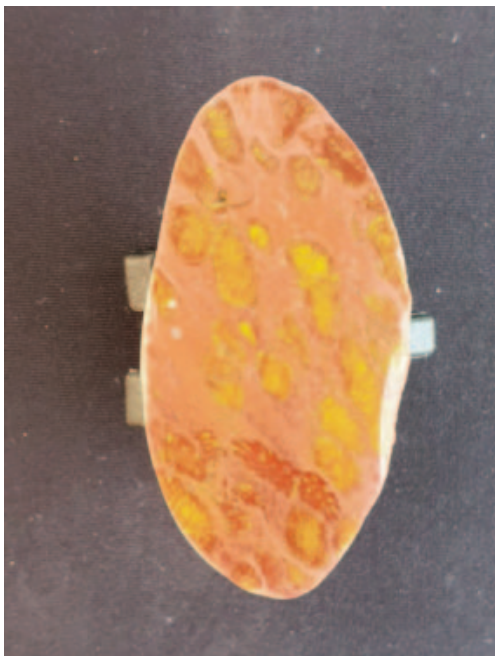
Figures 15–25 present a gallery of polished Devon Marbles prepared as described above.

[1] A personal on-the-ground survey for extant evidence of approximately 100 quarries in South Devon between 1998 and 2001. A paper-based survey of the Ordnance Survey map editions dated to the late 1880s confirms this to be almost universally true.

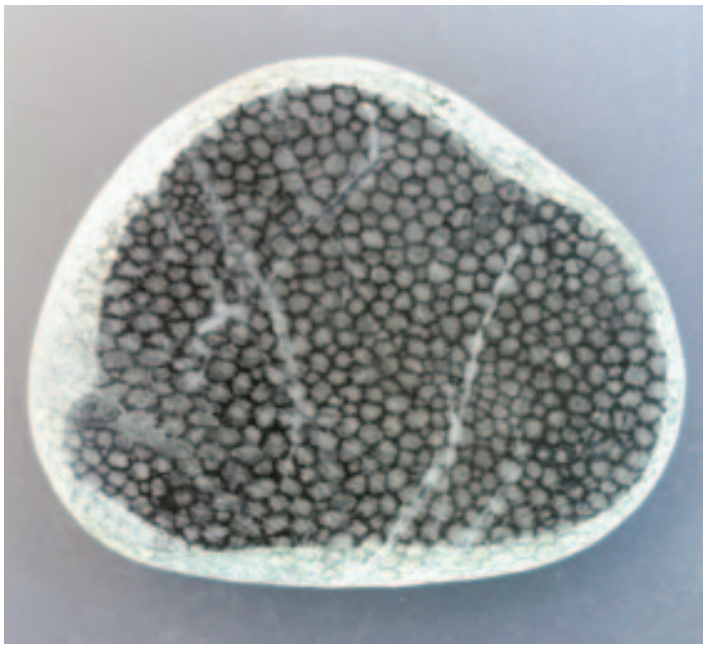
[2] Personal observation, August 2017.

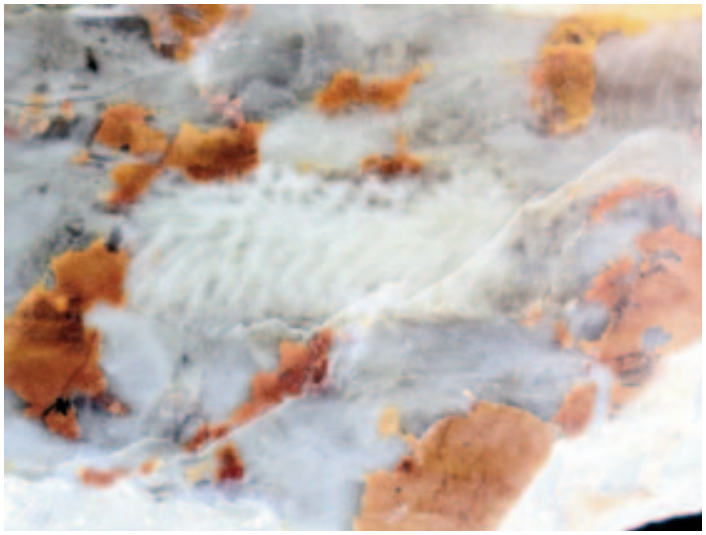
[3] Glassel (noun). A seaside pebble that was shiny and interesting when wet, and which is now a lump of rock; and which children nevertheless insist on filling their suitcases with after the holiday. From Douglas Adams and John Lloyd 1983 *The Meaning of Liff* (London: Pan Books / Faber & Faber), 58

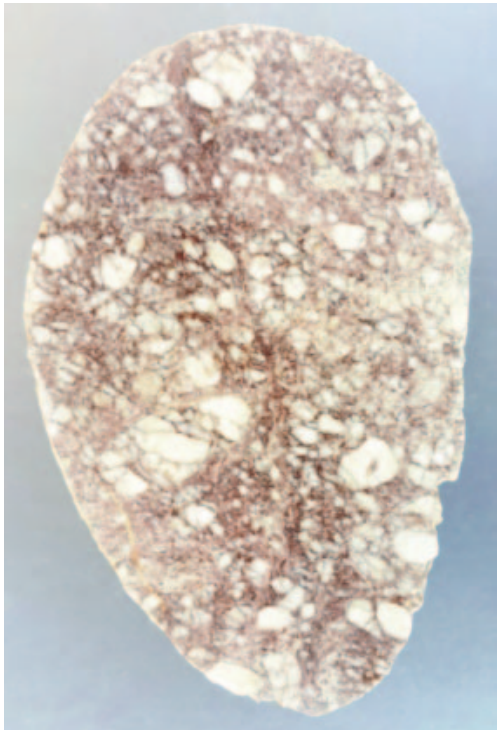
[4] Personal communication from Mr John Match.

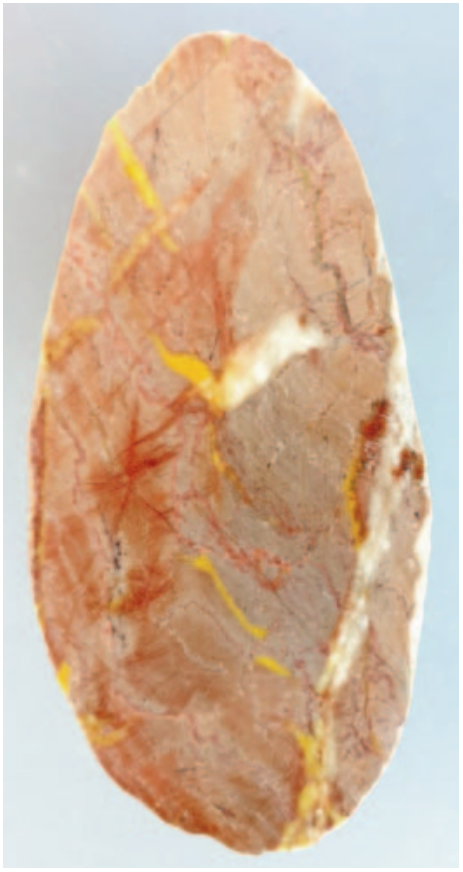


Figures 15–25 (bottom left and right are the polished stone and detail).









Book review

Di Capua, G., Bobrowsky, P. T., Kieffer, S. W. C., and Palinkas, C. (eds) 2020 *Geoethics: Status and Future Perspectives*. Geological Society, London, Special Publications 508 (ISBN 978-1-78620-534-4; 305pp; hardback £120.00)

This is the second volume on Geoethics by the GSL, describing how the field is maturing, and looking at anthropomorphic changes. There are 20 papers, starting with an introduction and explanation of how Geoethics now extends beyond the geological community.

The book is dedicated to Dr Jan Boon, a Dutch geochemist, and Director General of the Geological Survey of Canada, who then moved towards the social sciences on retirement and studied the relationships between mining companies and communities. His paper on sociology and mineral exploration is included in this volume. He was the Canadian Co-ordinator of the International Association for Promoting Geoethics, which was founded in 2020 and supported the publication of this book.

The first volume on this subject is *Geoethics: the Role and Responsibility of Geoscientists* (GSL SP 419, 2015) and in that volume the two editors, S. Peppoloni and G. Di Capua, defined Geoethics as follows:

• "Geoethics consists of research and reflection on the values which underpin appropriate behaviours and practices, wherever human activities interact with the Earth system.
• Geoethics deals with the ethical, social and cultural implications of geoscience knowledge, education, research, practice and communication, providing a point of intersection for Geosciences, Sociology, Philosophy and Economy.
• Geoethics represents an opportunity for geoscientists to become more conscious of their social role and responsibilities in conducting their activity.
• Geoethics is a tool to influence the awareness of society regarding problems related to geo-resources and geo-environment."

This book looks at that definition, and is certainly wide ranging and thought provoking,. It is a long way from pure geoscience. The papers investigate the global and local aspects of geoethics, including within the geosciences community, but start from the philosophy and recommend a nine-point charter for a responsible course for human development. In 'Geoscience, ethics and enforcement' O. Bonham and A. Waldie discuss the desired behaviours of geoscientists, and consider codes of conduct and enforcement. They lean towards recommending membership of professional bodes as a solution.

Then Dr Boon's paper starts a series of papers: on the practical application of mineral resource exploration and exploitation; the hydrosphere, groundwater and geoethical slope management; risk and its communication to the community; and climate change. The final paper looks at developing 'reasoning tools' for applying geoethics as we move from Earth to other planets and the stars, suggesting a focus on exploring rather than on exploiting other worlds. This final paper suggest fixing our home planet first.

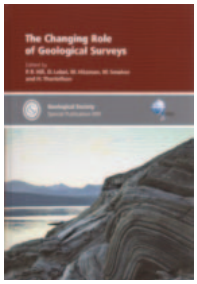
F. Oboni and C.H. Oboni's paper on holistic geoethical slope portfolio risk assessment introduces the concept of the Sapiezoic epoch, which describes — following the Anthropocene — when deliberate human activities change the planet. As I write this seems this epoch might not be as long as previous ones. The discussion is around the equity of resource allocation and the selection of the risks, and thus sites, to be addressed and the people who will benefit.

In 'Selling Planet Earth' I. Stewart and V. Hurth look at how to communicate current and future geo-environmental threats and challenges, and recommend marketing-led science communication, with purpose-driven communication.

These wide-ranging articles feel like just the start of a debate within wider society, and not just the geological community.

— John Lonergan, OUGS London Branch Organiser

Book review



Hill, P. R.,Lebel, D., Hitzman, M., Smelter, M., and Thorleifson, H. (eds) 2020 *The Changing Role of Geological Surveys*. London: Geological Society Special Publication 499 (ISBN (978-1-78620-476-9; 305pp; hardback £100.00)

This is a review of the current and future role of Geological Survey Organisations (GSOs), written by a combination of leaders and senior managers of GSOs from around the world. There are 22 papers, starting with a review and introduction, covering the current state of GSOs worldwide, the trends affecting them, examples of how they are adapting to change, and the use of big data and international collaboration. While population change is relatively predictable, societies' responses and technological change is disruptive and potentially chaotic.

The papers are divided into sections: Global trends, The state of the world's GSOs, Changing roles of GSOs, Data management and big data, and International collaboration. The first paper sets the context and is a review of geology in 2058. Key issues are the increase in population, and economic growth and consumption, and the uneven global distribution of resources, with increased competition. There is the suggestion that increasing efficiency will reduce the growth in the need for energy, but still involve a doubling of electricity demand, decarbonisation and an increased need for rare earth minerals. Water will be another key demand, and the land and oceans will be fully mapped, including seabed resources. This will involve politics and sustainability, an understanding of contamination to date, and cleaning it up.

All these changes are to be achieved in the context of climate change and ecosystems.

The later papers are from many parts of the world, seabed mapping in Norway, flexible and relevant geosurveys in Ireland, mineral innovation in Finland, data-driven earth science transformation, solving problems from state geological mapping in Russia, the future of the geoscience community in Asia, then ending with musings on the International Community of Geological Surveys and proposing a World Community of Geological Surveys. The Danish GSO sums it up in its move from classical geological services to environmental monitoring, energy transformation and advice on politically sensitive topics.

If there was any doubt over the breadth and future of the science and GSOs, this book will dispel it — a fascinating and wide ranging read!

— John Lonergan, OUGS London Branch Organiser

Neolithic and Bronze Age use of geological resources in Britain

Steve Woodward

Introduction

Until the end of the last glacial period the Radio 4 Shipping Forecast 'Dogger' region was dry land, connecting Britain to the Continent (Fig. 1). Extrapolating this map back in time, it appears also that the Thames may have been a tributary of the Rhine.

This article concerns how geological events gave rise to the availability of certain rock types, minerals and other niche substances in the British Isles, and how mankind exploited them.

Before examining some of early man's interactions with geology, to put things in perspective, Table 1 *(overleaf)* shows an overview of key archeological milestones within a period of time that began with 'Lucy', and ended with 'Pete Marsh', both early human ancestors of the Quaternary Period. 'Lucy' *(Australopjithecus afarensis)* was the 'pet' name given to the skeletal remains of specimen AL 288-1, a female hominin discovered in Ethiopia in 1974, dated 3.2 Ma. Nicknamed 'Pete Marsh', the Lindow Man was found in a peat bog near Wilmslow in 1984 and was dated *c.* 2000 years old. Although Lindow Man received much fame and notoriety, a similarly well preserved female head was actually discovered a year earlier and was dated 1750 years old, but somehow did not generate the same media frenzy. Soft tissue is well preserved in peat bogs because the dead or dying material beneath the living moss releases sugars and humic acids that consume oxygen and create anaerobic conditions.

Table 1 lists several pieces of evidence of occasional ancient 'human' presence in England (0.4 Ma to 0.5 Ma), but more permanent occupation was hampered by the ebb and flow of glacial ice sheets. Geologically speaking, our land became 'green and pleasant' only recently. After *c.* 3 million years of hominin evolution in warmer climes, Neolithic Man *(Homo sapiens)* took up permanent residence in the British Isles between 12 000 and 15 000 years ago; and for the first half of this period, it would have been possible for humans and animals to walk across what is now the English Channel, through a forest of epic proportions. Following accelerated glacial retreat, *c.* 7000 years later, sufficient ice had melted to flood the European land bridge, possibly resulting from a sub-marine event known as the Storegga Slides, when 180 miles of Norwegian continental shelf suddenly detached itself, initiating three substantial tsunamis. The possible trigger of the land slide was an earthquake, itself triggered by the catastrophic expansion of entrapped subterranean methane ice

Figure 2 Storegga tsunami deposits, bracketed by peat, Maryton on the Montrose Basin, Scotland (https://www.orkneyology.com/maeshowe.html).

Figure 1 The British Isles in the Palaeolithic Period (http://transition-townlouth.org.uk/Doggerland/doggerland.html).

($4CH_4{\cdot}23H_2O$), a cubic metre of which expands to form 164 cubic metres of gas.

The tsunami aftermath of alluvium deposits have been C^{14} dated *c*. 8200 Ka, at which time sea levels were 10–15 m lower than today (Fig. 2). Incredibly, the tsunamis' flotsam and jetsam can be found at elevations as much as 9 m above the current sea level. The event coincided with a 3°C drop in global temperature and referred to by climatologists as the '8.2-kilo year event', although there appears to be no connection between these two events. The temperature drop is believed to have been initiated by the death-throws of the Canadian (Laurentide) Ice Sheet when two glacial lakes in North America (named Ojibway and Agassiz) suddenly drained into the North Atlantic Ocean.

Doggerland has remained submerged now for *c.* 7000 years, but remnants of the ancient forest that spanned northern Europe can still be found, for example, beneath Redcar Beach where tree roots are exposed occasionally after the sand has been temporarily relocated by stormy weather to Spurn Point (Fig. 3) — usually following a particularly unfavourable shipping forecast.

Figure 3 Redcar Beach after sand had been temporarily relocated by Storm Emma, March 2018.

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INTERNATIONAL HISTORIC EVENTS			UK HISTORIC EVENTS
Great wall of china started	2,700		
	2,900	Iron Age	Callanish Stones - Lewis 2,900 - 2,600
	3,300		
	3,300	Bronze Age	
	3,520		Stone henge completed
Santorini Eruption	3,600		
Pyramids 4,575–4,150	4,200		Ness of Brodgar dismantled
	4,500 to 4,000		Ring of Brodgar
	4,500		Machrie Moor, Arran
	4,500		Beaker People
	4,600 to 4,500		Avebury
	4,600		Grimes Graves
	4,800		Maeshowe, Orkney
	5,000		
Earliest recorded city, Sumaria, Iraq.	5,000	Neolithic (New Stone Age)	Stonehenge outer circle relocated from Wales
Writing discover in Mesapotamia	5,200?		Ness of Brodgar
	5,370		Wheel and axle and plough invented
	5,500		Presills hils excavation (Stonehenge origin)
	5,500		Potters wheel. Welsh Dolmen
	5,750		Sea salt extrtaction - Boulby
	6,000		Beginnings of agriculture in Britain. Langdale axe industry, Cumbria +/- 500 years.
Salt mining, Bulgaria	6,700 ?		
	7,000		
Salt mining, Austria, Salzberg & Hallstatt			Dogger land flooded (8,200 Tsunami - Storegga Slide)
Giant Lemur extinct	8,000		
	9,000		Cheddar man
	10,000		
Nataruk, Kenya. Multiple homicide. 27 bodies killed with blunt instruments and obsidian tipped spears	10,000	Mesolithic (Middle Stone Age)	
	12,000		Ice age ends, July 19th (see footnote)
	12,000	Paleolithic (Old Stone Age)	
	25,000		Last glacial maximum (26,500 to 19,000)
Dogs domesticated	30,000		Start of last ice age (33,000)
	40,000		Homo sapien jaw bone - Kent's Cavern, Devon
Oldest Homo sapien fossils found in Jebel Irhoud cave, Morrocco	300,000		
Oldest Neanderthal remains. Spain's Atapuerca Mountains "Pit of Bones"	430,000		
	400,000		Neanderthals in Britain - Swanscombe - Kent
Wooden hunting spears	500,000		Leg bone & teeth found at Boxgrove, W Sussex. Homo heidelbergensis
	800,000		Denisovans/Neanderthals diverged from modern humans
	900,000		Stone tools discovered in Happisburg and Parkefield (Norfolk and Suffolk) dated 0.95 to 0.7 Ma, possibly Homo antecessor
Use of fire Homo Erectus (maybe earlier)	1Ma		
First species of Smilon (sabre toothed cats)	2.5 Ma		
Stone tool making well established	2.5 Ma		
Lucy (Australopithecus afarensis)	3.2 Ma		

Screenshot

Table 1 Key UK and International Milestones in Human Development (https://www.nhm.ac.uk/discover/first-britons.html). The various age divisions should be used with caution, as archaeologists are much divided as to where the divisions should be made. [For fans of Father Ted, however, according to a certain Father T. Crilly and Father D. McGuire, March 1986. Vol. 2-there is 'substantiated evidence' that the ice ended on July 19th: https://www.youtube.com/watch?v=uNTI5xN0SAI]

(Interestingly, before the skull of the Lindow Woman was dated at *c.* 1750 years, the level of preservation was so complete that the investigating authorities assumed the body to be that of Malika de Fernandez, whose husband had been under suspicion of murdering her *c.* 20 years earlier. Faced with the discovery of the skull, he confessed to the crime and was convicted of her murder as a result.)

Sodium chloride

Salt was probably the first mineral to be actively mined by humans and used in quantity. It is essential for survival, and can be used to preserve meat *(see below)*. The incumbent Neolithic population of Britain would have been keenly aware of the importance of salt, and of the fact that it could also be obtained from seawater.

Salt preserves strips of meat and fish by absorbing moisture from within, and without an electrolyte the rate of biochemical decay is vastly reduced. Salt also draws water by osmosis from the living cells of any food-borne pathogens (e.g. salmonella) and kills them.

Evidence of a unique Neolithic salt production unit (a saltern) has been discovered recently on the British north-east coast near Loftus (Fig. 4, *opposite*). A saltern is basically a fire pit wherein brine-filled ceramic vessels are placed to accelerate evaporation.

Figure 4 Neolithic saltern excavations, Street House, Loftus (https://www.cambridge.org/core/journals/antiquity/article/early-neolithic-salt-production-at-street-house-loftus-northeast-england/685000E2BB4CA0384CC8B4C7127D1F5).

The full extent of salt production at the site is still to be determined by geophysical surveys. The saltern had been constructed within the glacial boulder clay and previously was hidden beneath *c.* 0.5 metres of topsoil. Radiocarbon dating of a hazelnut shell dated the pit at 5977±30 years, with 95.4% accuracy (DOI: https://doi.org/10.15184/aqy.2021.25). At that time the sea level along this coastline was 2.5 m to 3 m lower than it is now, and based on local coastal erosion rates of *c.* 0.075 m per annum, extrapolating back 6000 years places the workings about 450 m inland. This evidence might explain the absence of other Neolithic salt-workings along the east coast, as they have been eroded away. Ironically, only a kilometre away there was more salt than Neolithic people could ever have imagined; the only problem being that it lies one kilometre beneath the surface within what is now Boulby Potash mine.

Knowledge of meat preservation was widespread among Britain's Neolithic inhabitants. The practice originated in the Middle East and came with Neolithic peoples as they migrated across Europe, but how humans first discovered this knowledge may never be known for certain.

One of the oldest sources of mined salt was at Hallstatt in Austria, and followed shortly afterwards in nearby Salzburg. The Hallstatt salt mine is located within the Upper Permian to Lower Triassic horizons of calcareous / limestone in the northernAlps.

Figure 5 shows the approximate extent of the Zechstein Sea, showing that Hallstatt and Salzburg would have been on dry land (red and green crosses). The salt deposits in these localities, like the evaporate minerals of the Boulby mines, were evaporite deposits, but formed as a result of evaporation on the fringes of the Paleo-Tethys Ocean in a region named the Hallstatt-Meliata Ocean (Fig. 6). Although of similar age geologically, the two bodies of water in question do not appear to have co-existed, despite the Zechstein Sea being dated 260 Ma to 252 Ma (https://core.ac.uk/download/pdf/81992255.pdf). Evidence of salt mining at Hallstatt dates back to more than 7000 years, when workings close to the surface were exploited, exposed by faulting during the Alpine Orogeny. Deeper salt veins were also mined, but not until the Bronze Age.

Stone axe manufacture

Second only to Stonehenge perhaps, nothing epitomises the Neolithic age more than hand-knapped stone cutting tools, and certainly the axe was central to the culture of that time. Such tools were used for clearing land, as weapons or for ceremonial purposes. The rock that most immediately springs to mind when thinking of Neolithic tools is flint, but flint was actually not widespread and several other rock types were also used. Figure 7 *(overleaf)* is a reconstruction illustrating how a typical axe made of stone from Langdale in the Lake District might have looked.

Figure 5 The approximate extent of the Zechstein Sea.

Figure 6 Location of Hallstatt-Meliata Ocean.

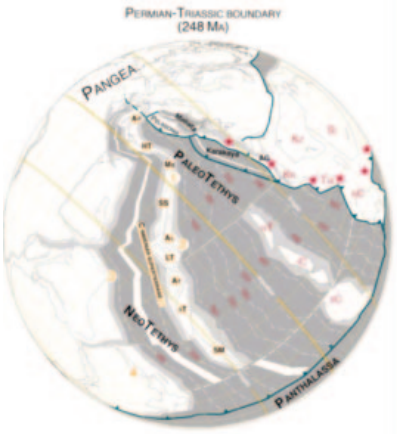


Figure 7 Reconstruction of a Langdale Neolithic stone axe hafted in a wooden handle (https://freedomtoteach.collins.co.uk/neolothic-know-how-great-langdale-axes/).

The central massif of the Lake District around Great Langdale and Scafell Pike was one of the major locations for the production of Neolithic stone axes (https://www.cambridge.org/core/journals/proceedings-of-the-prehistoric-society/article/abs/neolithic-quarries-and-axe-factory-sites-of-great-langdale-and-scafell-pike-a-new-field-survey/9296D3D6C521355837ED70FA234A9FFF). A survey of this area in the 1980s identified 566 distinct working sites, and the quantity of axe-making debris,, particularly in the Langdale area (OS Ref. NY274072. Ambleside), confirms that production took place on a large scale. Axe-making appears to have been done at the Langdale site for more than 1000 years (6000 +/- 500 years ago), at which time the population of 'Britain' has been estimated as *c.* 200 000.

The favoured rock types for axe-head manufacture in the Langdale area are colloquially called 'Greenstone' and 'Hornstone', and axes made of this stone have been found as far afield as north-east Scotland, Cornwall, and all along the British east coast. Most axes show signs of heavy use, but occasionally pristine examples are found, suggesting that these were for ceremonial use or gifting. At Langdale, only the 'rough-outs' were made. The highly polished items were usually finished on the western fringes of Cumbria. It has been estimated that it took up to 70 hours per axe.

Although also found on the scree (talus) slopes, the favoured location for Greenstone was at the top of majestic Pike O'Stickle, perhaps because of its very inaccessibility (Fig. 8). The Greenstone is described in various sources as a narrow 'vein' of tuff, and Horrnstone as a very fine-grained volcaniclastic siltstone, known as the Seathwaite Fell Formation. Clearly, a volcanic tuff of compacted volcanic ash would have been an unsuitable material from which to fashion an axe head. However, the original volcaniclastic 'sediments' were later lithified *(see below)*.

Figure 8. Pike O'Stickle, Cumbria (OS Ref. NY273073; height 709 m).

Lake District evolution in brief

(https://www.livescience.com/29936-england-lake-district-geology.html)

Approximately 500 Ma, the oldest rocks in the area were sediments at the bottom of the then equatorial Iapetus Ocean. These sediments eventually became the Skiddaw Group, exposed in the northern third of the Lake District. The tectonic collision associated with the closure of the Iapetus Ocean *c.* 450 Ma initiated a period of intense volcanic activity and created the Borrowdale Volcanic Group, which forms the base of the mountainous middle of the Lakes.

The Scafell range is part of what was, at that time, a 15 km diameter volcanic caldera, which eventually filled with water to form a large lake, probably greater in volume than lake Windermere.The surrounding area was still active volcanically and the subsiding lake became a repository for volcaniclastic sediments, such as those that later became the Greenstone (Fig. 9) and Hornstone.

The southern third of the Lake District consists of slates, siltstones and sandstones, known as the Windemere Group. These rocks possibly formed at the bottom of the Paleo-Pacific Ocean *c.* 420 Ma. Then, at 400 Ma, the Caledonian Orogeny again exhumed the rocks, forming a mountain range that could have eclipsed the modern Himalayas. After millions of years of erosion, in the Early Carboniferous at 350 Ma the land was once

Figure 9 Examples of Greenstone, possibly exhibiting eutaxitic texture (http://nora.nerc.ac.uk/id/eprint/3234/1/RR01007.pd).

Figure 10 Pike O'Stickle highlighted on BGS Sheet 38: Ambleside Solid and Drift (1996) (© British Geological Survey).

again at the bottom of an ancient ocean, known as the Panthalasa Ocean. Then some 280 million years ago, the Variscan Orogeny again uplifted the area, and within the last two million years Pleistocene glaiers advanced and retreated multiple times, carving deep valleys into the impervious rocks, which then later filled with meltwater and rain.

(For a comprehensive description of Cumbrian geology see Branney, Mike J. 1999 *The Caledonian Igneous Rocks of Great Britain*. Joint Nature Conservation Committee, chapter 4.)

The British Geological Survey Ambleside sheet 38 (1:50,000) does not show the Greenstone or Hornstone, but there is one reference in the key to 'Stickle Pike Rhyolite' listed as part of the 'Lickle Formation'. This is described in detail in a survey as "Stickle Pike tuff member, pale-weathered, eutaxitic to parataxitic, rhyolitic lapilli-tuff (densely welded ignimbrite)" (http://nora.nerc.ac.uk/id/eprint/3234/1/RR01007.pdf; note: eutaxitic describes the texture of fine wavy layer within igneous rocks, but 'parataxitic' is not defined in *The Oxford Dictionary of Geology and Earth Sciences*).

There is also no mention in the map's key of the Caldera Lake series. The Seathwaite Fell Formation is listed, but elsewhere. I believe the Caldera Lake series may be part of the Seathwaite Fell Formation. The map colours are difficult to reconcile with the key in the Pike O'Stickle vicinity in either the 1996 or 1998 editions of the map (Figs 10 and 11).

Below the Pike O'Stickle summit there is a small man-made cave, possibly a source for quarrying Greenstone for axe roughouts (Fig. 12).

Grimes Graves

Stone axes have been made from many other rock types around the world, such as obsidian, jadeite, porcellanite chert, and various fine-grained igneous rocks, but in certain parts of Britain flint was the most highly sought-after raw material.

Grimes Graves in Norfolk was one of humankind first industrial-scale mining operations (Figs 13 and 14, *overleaf*). Excavation for flint began here in the Neolithic *c.* 4600 years ago, and large-scale mining continued in the Bronze Age. The excavation of flint nodules in the Neolithic began by sinking pits *c*. 4 m in diameter

Figure 12 Cave below the Pike O'Stickle summit, a Neolithic cave?

Figure 11 Pike O'Stickle highlighted on BGS Sheet 38: Ambleside Solid and Drift (1998)(© British Geological Survey).

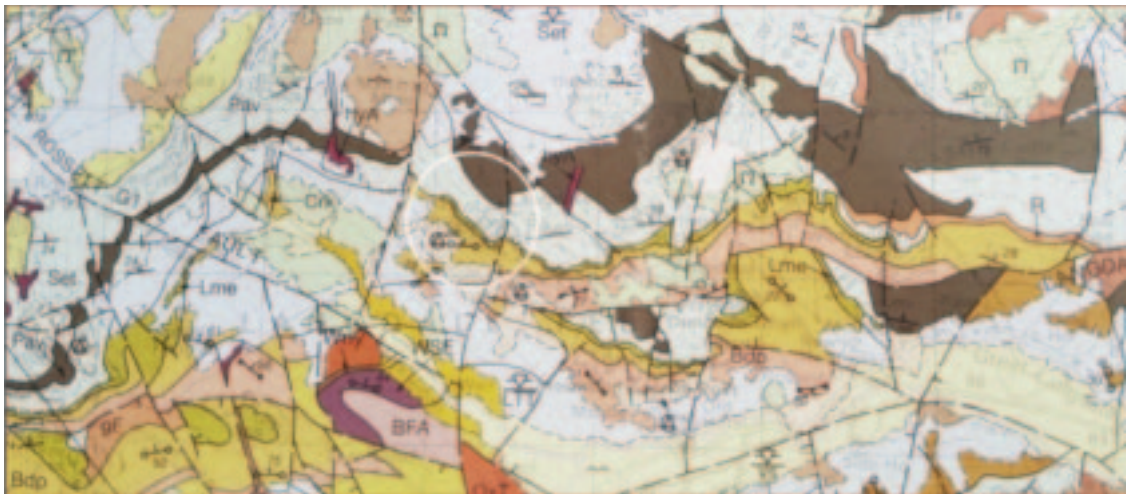


Figure 13 Aerial view of the Neolithic flint mining pits at Grimes Graves, Norfolk.

Figure 14 Sectional reconstructive representation of flint mining in an individual pit at Grimes Graves.

to a depth of *c.* 12 m. It has been estimated that up to 60 tons of flint were extracted per pit. As each successive pit was exhausted, it would be back-filled before work started on a new pit. Subsidence has caused the pit surface centres to sink, and the site has 430 pits, closely spaced circular depressions in the chalky grassland.

As well as at Grimes Graves, there is a similar Neolithic excavation for flint at Cissbury, West Sussex.

The Cretaceous Period was, fundamentally, a period of global warming at a time when there was no permanent ice on the planet and when forest cover extended to the poles. The absence of ice resulted in sea levels of >100 m higher than now, owing to an average global temperature of just 4°C warmer than it is today! This also explains why Cretaceous limestone (chalk) is white whereas earlier limestone deposits were a muddy grey. The sea level rises created longer continental shelves, which were far removed from the effects of land erosion and alluvial deposition and resulted in the sea water being particularly clear and clean. There was also less exposed land, further reducing the amount of erosional deposition into the oceans. The Cretaceous seas were abundant with life and the sea floor an extremely active environment, so any organic matter was quickly consumed or broken down, resulting in a pure lime mud formed almost entirely from planktonic skeletal remains.

The flint nodules were not buried, but rather were precipitated somewhat later. They originated from the silica-based skeletal parts of certain deceased marine organisms that accumulated on the seabed. What is not clear is why the flints tend to occur in discrete layers. David Bone of West Sussex Geology describes the formation of flint thus (http://snpr.southdowns.gov.uk/files/additions/For%20how%20flint%20is%20formed.htm):

Organisms such as sponges (on the macro scale) and radiolaria / diatoms (on the micro scale) use silica from sea water to manufacture the biogenic opal[,] which forms their skeletons. When the organisms die and the organic parts decay, the microscopic silica is scattered on the seabed and becomes incorporated in the accumulating sediment.

At depths of 1–5m within this sediment, the biogenic opal breaks down, enriching the water between the sediment particles (sediment pore water) with silica.

At sediment depths of less than 10m, there is an oxic-anoxic boundary where hydrogen sulphide rising from the decomposing organic material within the sediment diffuses upwards [and] meets oxygen diffusing downwards from the water column above. At this interface, the hydrogen sulphide is oxidised to sulphate[, producing] hydrogen ions as a by-product. The hydrogen ions lower the local pH, dissolving the chalk and thereby [increases] the concentration of carbonate ions. These act as a seeding agent for the precipitation of silica.

Silica precipitates by the molecule-by-molecule replacement of chalk. The silica is initially in the form of crystalline opal, but gradually transforms to quartz (flint) during later burial and with time.

The chalk sea bed is deeply burrowed by many different organisms, such as shells, echinoids and worms. Some of these burrows are quite deep or branching, or have open living spaces. The burrows fill with sediment after the organism has died, this is slightly different material from the sediment around it. These filled burrows act as preferential conduits for the chemical reactions that create flint nodules within them. There are two possible explanations for why flint forms in bands or layers. First, because chalk sedimentation occurs in cycles; and second, because the process described above exhausts the silica within a given depth of sediment; thus, flint formation can only recommence when there is enough silica to start the process again.

Henges and stone circles

The transition from a hunter-gatherer to an agrarian lifestyle appears to have created a great deal of free time, as judged by the abundance of henges, burial mounds, stones circles and fortifications that were built by our Neolithic ancestors. Despite the fact that early farming is known to be labour-intensive, there was obviously sufficient free time to devote to much

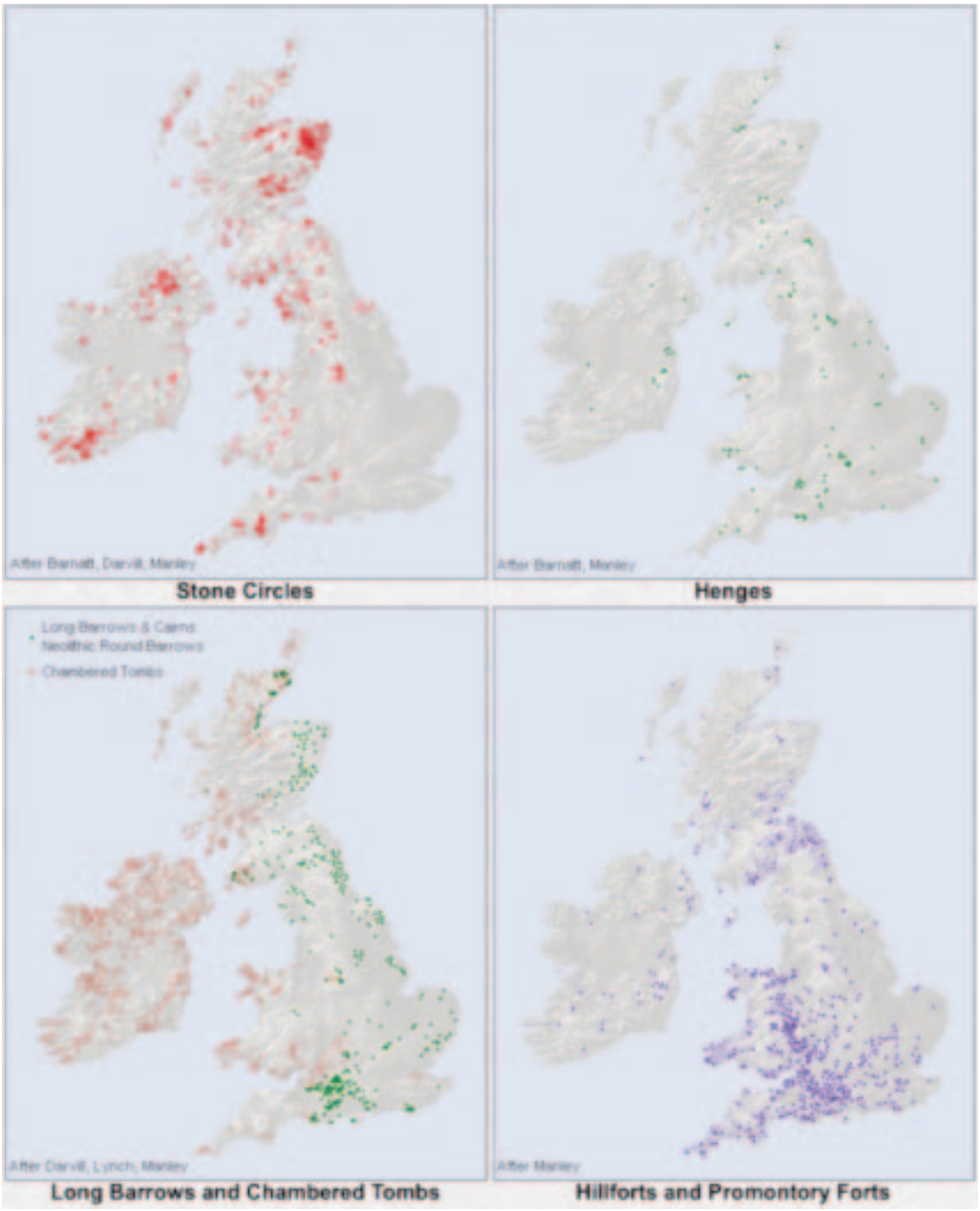


Figure 15 Maps of he locations principal stone and henge monuments (www.stone-circles.org).

monument-building. Figure 15 shows the main locations where different types of stone-related construction were undertaken. (For a more complete list, including tombs, fortifications and other structures, see www.stone- circles.org — a website with more than 600 entries, but which includes Bronze Age and Iron Age constructions.)

The term 'stone circle' is self-explanatory. The term 'henge', however, is not. A henge is actually an earth work of some type and may or may not have stone circles associated with it. The most well known stone circles are probably those in Wiltshire at Avebury, and of course Stone Henge itself. More interesting, some might argue, are the Neolithic constructions that were built much farther north, such as on Orkney (Fig. 16, *overleaf*).

Underlying Orkney, but exposed only rarely, are the roots of the Caledonian Mountains ,which formed when Laurentia collided with the micro-continent Avalonia in the Caledonian Orogeny (*see* Fig. 30). The two landmasses were originally separated by *c.* 7000 km of Iapetus Ocean, hence closure was a slow process that spanned *c.* 150 Ma from the late Cambrian to the middle Devonian. What would eventually become the northern part of Scotland was on the coast of Laurentia, with the rest of the UK on Avalonia (by this time separated from the Gondwana supercontinent). The Orkney sandstone units we see today were deposited in the mid- to late-Devonian in Lake Orcadie, a vast freshwater lake within the wider Orcadian Basin, adjacent to the Caledonian Mountains. The basin was formed by crustal extension. So, the Old Red Sandstones (ORS) of Orkney are mostly fluvial / lacustrine eroded mountain deposits, and with some of the younger sandstone units are aeolian-formed. Deposition continued into the Permian, but any rocks younger than *c.* 400 Ma have since been lost through weathering and erosion by glacial processes.

Variations in climate resulted in corresponding variations in deposition rates that periodically interrupted the sequence, such that Orkney sandstones are referred to as Flagstones because of their natural tendency to cleave along preferred parallel planes.

The sandstone sequences exhibit a marked cyclicity in their sedimentation: 86 such cycles have been identified, interpreted as regular changes in lake level caused by Milankovitch cycles. The bedding plane weaknesses, together with other naturally occurring transverse cracks, created a ready supply of parallelogram or trapezoid building blocks from which the Neolithic Orcadians constructed a variety of buildings and other stone monuments. The largest construction is at the Ness of Brodgar complex, which consist of 14 bespoke stone dwellings and other buildings within a perimeter wall more than 3 m thick (Fig. 17, *overleaf*).

Skara Brae

Of all the stone monuments on Orkney, perhaps the most iconic is Skara Brae (Fig. 18, *overleaf*). Radiocarbon dating confirms the oldest permanent dwellings here were 5500 years old. The Neolithic population in the far north was greater at this time than elsewhere in Britain. Climatic conditions were milder, making short-season agriculture possible. Neolithic Orcadians used the local stone and its cleaving properties to good effect, producing sandstone blocks to construct their dwellings — eight of which were occupied between *c.* 5180 and *c.* 4500 years ago. The site was discovered in 1850 when severe storms removed the overlying sand dunes, but not excavated until 1927–30 by V. Gordon Childe.

Other mineral resources utilised at the site include limonite, galena and haematite, from which various shades of ochre were made for painting. Specimens of polished haematite nodules suggest that they were also used for finishing leather.

Figure 17 The Ness of Brodgar excavations (https://archaeology.co.uk/articles/features/the-ness-of-brodgar.htm).

Figure 19 Maeshowe: exterior and interior views. Interior rear wall illuminated by the setting Sun; uppermost roof has been reconstructed.

Figure 16 Neolithic features on Orkney (https://www.nessofbrodgar.co.uk/ness-neolithic-trail/).

Maeshowe

Another significant construction on Orkney is Maeshowe, a chambered tomb encased within an earth mound *c.* 35 m in diameter and 7 m high (Fig. 19). The interior chambers were constructed using ORS without mortar The slabs were corbeled to create a domed ceiling. The four ORS corner stones, although appearing to provide support, serve no structural purpose and may have been part of an earlier stone circle. The tomb's opening

Figure 18 Skara Brae, on the mainland west coast of Orkney (https://www.orkney.com/news/lonely-planet-hitlist).

on the west wall is aligned such that it channels in sunlight from the setting winter solstice Sun. It has been estimated that it may have taken 100,000 man-hours to complete its construction. It has been suggested that one reason that Neolithic Orcadians had become so adept at stonemasonry is because they had felled most of the trees.

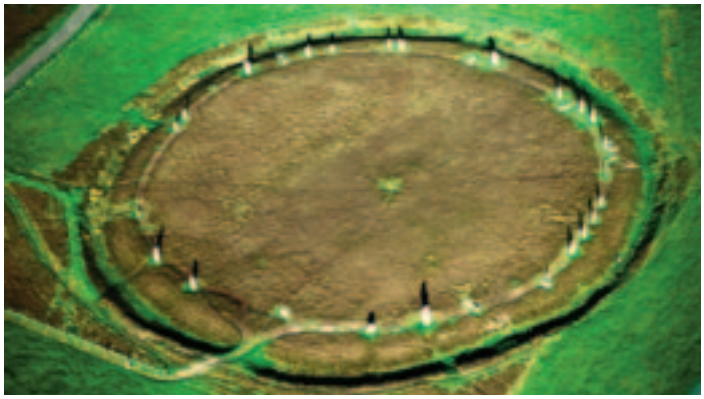


Figure 20 The Stones of Stenness, making artistic use of the ORS rakish fracture angles.

Bryn Cell Ddu

Pronounced 'Brin Kethley Dee', meaning 'Mound in the Dark Grove', this smaller chambered monument is situated on the south-east coast of Anglesey *c.* 1 km from the Menai Straights. As at Maeshowe, its entrance passageway is orientated to catch the summer solstice sunlight, where it illuminates a blue schist pillar and rear wall panel (Fig. 21).

The blue schist was quarried on Anglesey and was selected for its iridescent properties, which stem from its abundant mica content. Conventional schists are metamorphosed mudstones or shale, but the basis of the unique Anglesey blue schist is

Figure 21 Bryn Celli Ddu Neolithic burial chamber an Anglesey, age c. *5000 years (by Jensketch — Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=69530137).*

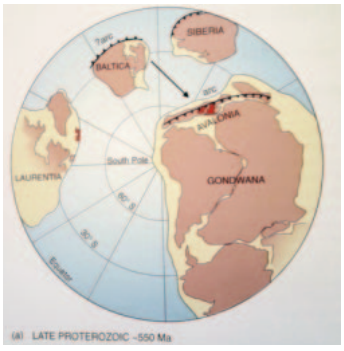
basalt, in which its blue colour results from the presence of glaucophane — an amphibole (Na, Mg, Fe, Al silicate, plus mica, etc.) Schist is an indicator rock type for a subduction zone of high temperature and low pressure, as its formation requires rapid subduction followed by equally rapid exhumation. It has been dated at 580 Ma, at which time the southern half of Britain was at the South Pole and was part of Avalonia, where the Anglesey region was influenced by the adjacent subduction zone (Fig. 22).

Orkney's stone circles

The Stones of Stenness and the Ring of Brodgar are on either side of the Ness of Brodgar, a narrow spit of land between two lochs (*see* Fig. 16). Dated 5400 years old, the Stones of Stenness might be the oldest stone circle in Britain (Fig. 20). With other similar constructions, its purpose remains unknown.

Little is known about why Bryn Celli Ddu was built and what may have been ceremonies may have been performed there. Other than that it was a burial chamber or a place of ritual cremation. As with other Neolithic sites, the chamber was later later used by Welsh Druids. From about the time of the Roman occupation of Britain the site became legendary for its Wicker Men. One legend claims that the Romans were deterred from crossing the Menai Straights by the burning of a substantial wicker man, complete with human occupants (Fig. 23, *overleaf*).

Figure 22 Palaeogeographic map showing locations of England and Wales c. *550 Ma (SXR 260 Geological History of the British Isles; © The Open University).*



Long Meg and her Daughters

This Cumbrian stone circle is Bronze Age in date. Clearly, the name is a more recent appellation, as is the path to the nearby church (Fig. 24) *overleaf*.

Myths and legends about this monument abound, but otherwise little is known about it except what may be inferred from the deliberate positioning of certain quartz-rich 'daughters'. These appear to be aligned with key lunar and solar events, making it, perhaps, some form of calendar.

Figure 23 A wicker man, complete with occupants (Wikimedia Common).

The stone known as Long Meg herself is significantly taller than her rounded and squat 'daughters', and also unique in that she is the only red sandstone member. Beneath the substantial Devensian glacial till layer here. the underlying rock is early Triassic sandstone of the St Bees Formation (Durham University Report 3132 December 2013 Durham University), which is exposed locally in river cuttings (Sherwood Sandstone Group). Not too far distant, exposures can also be found of Permian New Red Sandstone (Appleby Group, Penrith Sandstone Formation). In terms of the geological setting, the parent sandstone (whichever it was) originated in the desert to the west of the Zechstein Sea.

The New Red sandstone is a popular building material in this area. Certainly, most of the older and more grandiose halls and dwellings are distinctly red. Even the farmers' drystone walls, despite having weathered to a dull grey, have a surprisingly red interior; and newly built walls are noticeably red (Fig. 25)!

Figure 25 A New Red Sandstone Wall (pun intended).

The *c.* 69 daughter stones are described variously as rhyolitic or granite erratics, having being deposited in this locale by retreating glaciers, but I was unable to verify this. However, one of the daughter stones has two identical fossils (Fig. 26).

Figure 24 Long Meg and her daughters near Penrith, Cumbria (Wikimedia.org/wiki/File:LongMegAndHerDaughters (SimonLedingham) May2005).

Figure 26 One of two identical fossils found in a supposedly igneous rock. The depressions are about the size of a modern-day razor shell clam.

Dolmens

Dolmens are the oldest type of stone monuments in Britain. They are examples of Neolithic people's first efforts in the art of megalithic stonecraft and they predate the beginnings of Stonehenge by *c.* 500 years. Although little else is known about them, or, in fact, the origin of the word 'dolmen', they are mostly interpreted as burial chambers that were covered by earthen mounds. What usually remains now is a huge slab of rock balanced atop two or more vertical members. Dolmens are found throughout many European countries, one of the largest known being Pentre Ifan in Pembrokeshire (Fig. 27). There does not seem to have been a concerted effort to identify the rocks from which they are made more closely.

Figure 27 Pentre Ifan, a 'portal' dolmen near Newport, Wales.

Figure 28 Stone reconstruction, as it would have looked in its final form (https://www.english-heritage.org.uk/visit/places/stonehenge/history-and-stories/building-stonehenge)

Stonehenge

Stonehenge is possibly the most iconic of the Neolithic constructions in England and it was only recently that Prof. Mike Parker Pearson (UCL) literally unearthed a new 'missing link' in the henge's long history.

The earliest archeological evidence of activity at the Stonehenge site is dated *c.* 8000 years ago when the henge was no more than a circular ditch and mound feature with a ring of 56 wooden posts. All that remains of the wooden posts today are the 56 'Aubrey Holes', named after their discoverer, 17th-century antiquarian John Aubrey.

It was not until towards the end of the Neolithic that the monument finally reached the form represented by the ruins left today (Fig. 28). In this final form, it can be seen that there is an inner circle of smaller pillars, somewhat dwarfed by the five surrounding trilithon 'portal' stones.

Two main types of stone were used in the long, multi-phased construction of Stonehenge (https://www.english-heritage.org.uk/visit/places/stonehenge/history-and-stories/building-stonehenge). The smaller bluestone pillars are a type of dolerite and the larger sarsens (abbreviation of Saracen Stone) are a silcrete. The sarsen silcrete blocks can be found all over the south of England and were thought originally to have been brought 32 km from the Marlborough Downs. More recent geochemical survey indicates that they were most probably sourced from the West Woods, only 24 km to the north (https://advances.sciencemag.org/ content/6/31/eabc0133). Silcrete is a relatively young rock formed in the Palaeogene–Eocene from anastomosing river channels that drained north-west to south-east, creating belts of sand over a clay-rich coastal floodplain. They often occur as discrete, isolated blocks because the parent sandstone underwent patchy silicification during Palaeogene–Eocene global warming dated 55.5 Ma. Silicification, together with the presence of root fossils, indicates that the sandstones were near the surface and subject to cyclic evaporation, which concentrated the silica present in the ground water. Being in the same vicinity, the sarsens were also used by Neolithic farmers in the construction of the Avebury Stone Circle. Each sarsen weighs *c.* 25 tonnes, and in contrast the bluestones a mere 1.5–2 tonnes each.

Other types of stone used at Stone Henge in smaller amounts are tuff, rhyolite and calcareous ash; and the 30-tonne so-called 'altar stone' is sandstone of a type found in the Black Hills of southeast Wales.

It has been known for some time that the Stonehenge Bluestones were quarried and transported from somewhere in the Preseli Hills of west Wales (Fig. 29). However, more recently, Prof. Mikael Parker Pearson, using advanced geochemical identification techniques, was able to identify the two parent bluestone quarries. The largest quarry was *c.* 225 km (140 miles) from Stonehenge in an outcrop on Carn Goedog tor on the north slope of the Preseli Hills (Fig. 30, *overleaf*), and was the main source of Stonehenge's spotted dolerite. The second quarry was close by in the valley below Carn Goedog, in an outcrop at Craig Rhos-y-felin, and was identified as the source of the rhyolitic material. The discovery of the quarries overturns a previous theory that the stones might have been transported by glaciation.

As can be seen in Figure 31 *(overleaf)*, the dolerite intrusion has basalt-like columnar joints, making it relatively easy to split into blocks by using wooden wedges to work and split the blocks along natural weak lines.With the discovery of the locations of the Stonehenge quarries came another important discovery: hazelnuts found in the excavation were radiocarbon dated and revealed that the workings predated the stages at Stonehenge using bluestones by *c.* 400 years! This new evidence raised a number of new questions, and a theory was soon suggested that the bluesstones were used to construct a local stone circle, which later was dismantled and relocated in Wiltshire. Using aerial mapping and ground radar, the UCL team set about searching for the original stone circle and found a number of candidate sites. However, when traces of the original holes for the bluestone settings were excavated they were found to be associated with a much later Iron Age settlement.

Figure 29 Map showing locations of Stonehenge, the Preseli Hills in west Wales and possible transport routes for bringing the bluestones.

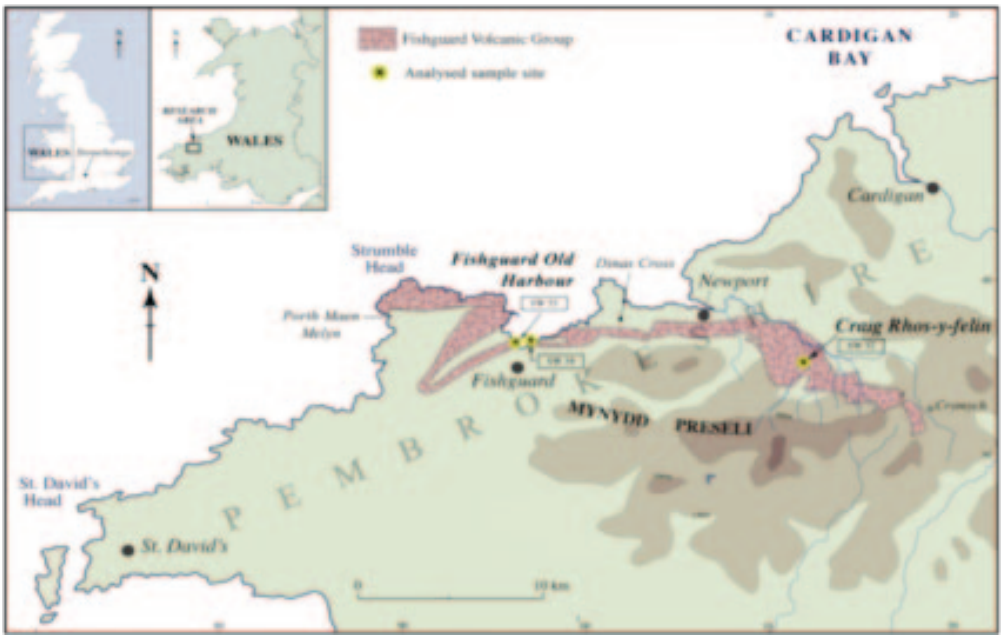


Figure 30 Bluestone quarry locations in the Preseli Hills (blog.geolsoc.org.uk/2016/11/18/the- mystery-of-stonehenges-bluestones/).

A second possible site located by the survey was at Waun Mawn on a tract of land below Cnwc yr Hŷdd hilltop near the quarry sites. Excavations here and the use of optically stimulated luminescence (OSL) revealed the ring of trace holes to be of the right date.

The physics behind OSL is complicated but can be summarised as a technique that can detect when the Sun last shone on any quartz grains. Obviously, it would be pointless if, on the day of testing, the Sun were to shine on the freshly exposed quartz grains, so to prevent this happening retrieval of soil samples from within the post holes was undertaken under a black-out cover. OSL indicated the selected quartz grains had been buried for 5300 years. In addition, the excavated post holes at Waun Mawn formed a stone circle of 33.5 m (110 ft) 110, exactly the diameter of the raised mound that surrounds Stonehenge.

Some geological background

As seen earlier in Figure 22, and now depicted in more detail in Figure 32, the subducting ocean crust of the area known as Avalonia was on the margins of the shrinking Iapetus Ocean, a closure that would eventually unite England and Wales with Scotland. The Iapetus Suture, however, is indistinct and not actually aligned with the Scottish border — it is said to follow the Solway Firth. Bluestone is a generic geological term used to describe any doleritic igneous dyke or sill that is dark in colour, fine to medium grained and mafic (the olivine / pyroxene end of the igneous spectrum).

The Fishguard Volcanic Group, in which such igneous rocks are found, was initiated by 'text-book' vulcanism associated with a subducting ocean crust. The group is 1800 m thick and consists of lavas, breccias, tuffs and associated volcaniclastic 'sediments' that were laid down in the marine environment of the Welsh Basin during the Llanvirn series of the Ordovician period, dated 480 Ma. U-Pb dating of the Fishguard Volcanic Group yielded dates between 467.3 Ma and 458.4 Ma (https://blog.geolsoc.org.uk/2016/11/18/the-mystery-of-stonehenges-bluestones/). Zircon crystals from the Stonehenge samples yielded an age of 462.20 +/- 0.26 Ma.

Figure 31 The columnar-jointed Cam Goedog exposure in the Preseli Hills (www.southampton.ac.uk/news/2019/03/stonehenge-bluestones.page).

Figure 32 Closure of the Iapetus Ocean (from SXR 260 Geological History of the British Isles; © The Open University).

The fact that the bluestones were relocated 225 km (140 miles) says a great deal about how well-connected Neolithic people were. Substantial north–south migrations are also indicated by the numerous and non- indigenous animal bones discovered on Orkney when the dwellings at the Ness of Brodgar were largely abandoned *c.* 4500 years ago. It has been hypothesised that the site was a holy place of pilgrimage, and that Orcadian Neolithic people may have initiated the fashion for stone circle construction; certainly, their dwelling designs were copied elsewhere.

Neolithic conclusions

The question as to why and how the Waun Maun circle was dismantled and relocated to the Wessex plains remains largely unanswered. The monumentality of both Stonehenge and the Ness of Brodgar's central buildings, and the amount of labour and organisation necessary to construct such structures, suggest their undoubted importance to the Neolithic peoples who made them. Together with evidence for migrations, possibly holy pilgrimages, proving the interconnectedness of Neolithic peoples in Britain through millennia it seems we still have much to learn about Neolithic Britons' use of their geological landscape.

Neolithic culture and technology was the end product of a miraculously complex and often serendipitous sequence of cosmological, geological and biological events. One of the small but essential 'miracles' that occurred on this journey was the domestication of bread wheat, which underpinned Neolithic farmers' transition from hunter-gatherer to agriculturalist. Approximately10 000 years ago in the Middle East what would eventually become grown wheat was no more than a spindly wild grass, but a mutation occurred when it became 'crossed' with another grass: emmer wheat (J. Bronowski 1973 *The Ascent of Man*). This fertile hybrid was still a grass and as such it sowed itself on the wind such that our hunter-gatherer ancestors found it in abundance. Sometime before *c.* 8000 years ago, a third mutation occurred in this 'wild wheat', which might have been the death knell for the species were it not for the intervention of humans. The plant was similar to our modern wheat, and had grains that could not easily be transported by the wind. The grains would have rotted where they fell or been scavenged, but with human intervention through collection and eventual deliberate cultivation of emmer wheat the species prospered. In terms of evolutionary success, bread wheat could be considered the outright planetary winner, causing at least one commentator to consider our evolutionary symbiosis the other way around, envisaging wheat as having 'engaged' humans to proliferate itself around the planet — who's farming whom? (Y. N. Harari 2011 *Sapiens: a Brief History of Humankind*). Similarly, large 'subaerial' fruit and vegetables such as squash and pumpkins relied for their proliferation on being trampled by foraging megafauna. This role was also shared by humans, not least because they played a significant part in the demise of megafauna.

Figure 33 Skull pierced by a bronze spearhead (@arkeomega) on Instagram, Aphroodisia Museum, Turkey).

The Bronze Age

In discussing the Bronze Age, to examine ancient Britons' use of geological resources I will focus on the major copper and tin deposits in England.

The Bronze Age spanned the period roughly from 5000 to 3300 years ago (3000–1300 BCE). As we have seen, although much of the population in Britain lived in small and isolated settlements, great feats of stone construction were accomplished, in scale and complexity matching similar construction elsewhere in the world — for example the construction of the Pyramids of Giza in 2350 BCE). There is also evidence of well-established international marine and land trade routes, together with a great deal of rivalry and conflict. During this time, the discovery of the use of copper and bronze artefacts played a key role, not least for making effective weapons (Fig. 33).

Copper

Copper ores have been extracted from numerous locations in and around the UK and Ireland, but probably the largest and best-known Bronze Age excavation is at the Great Orme in North Wales (Fig. 34). The copper ores are found within Carboniferous Limestone, more precisely *c.* 330 Ma within the Visean subdivisions (Asbian to Early Brigantian). The Orme limestone covers an area of *c.* 4 km × 0.8 km, and in places is up 200 m thick.

Figure 34 Great Orme headland, north Wales and the Great Orme copper mines (www.greatormemines.info/gallery/).

Figure 35 The location of the Great Orme Limestone on the North Wales shelf (blue arrow) (OU SXR 260, plate 7; © The Open University).

The limestones were deposited in the shallow seas of the then equatorial Rheic Ocean. Figure 2 shows that the sediments are 'punctuated' by a series of dark parallel bands. Inspection of these features has revealed them to be paleosols and surface of karstification — evidence of cyclic exposure to the atmosphere owing to changes in sea level.

Figure 35 shows that the Great Orme Limestone was deposited on the North Wales shelf, one of several carbonate platforms that formed in the shallows of the Rheic equatorial seas. Carbonate deposition ceased during the late Brigantian, when the basin was inundated by the sediments of a large river system flowing from the adjacent Brabant Massif and buried the limestone under 1–1.5 km of shales, siltstones and coarse sandstones. Eventually this gave way to the swamp environment that 'seeded' the Westphalian coal measures. At this time flora and fauna proliferated on land at an accelerated rate owing to high oxygen levels (up to 35%). However, trees, once fallen, did not decay as they would now, because no creatures yet existed that were capable of breaking down lignin.

The next major geological event was the Variscan Orogeny, starting in the Late Carboniferous when the Rheic Ocean was closed by the collision of the continents of Laurentia (to the north) and Gondwana (to the south). This closure uplifted the Orme Limestone. The collision compression was followed in the Variscan by regional tectonic extension across Wales and northern England, resulting in reburial of the Orme Limestone under 1 km of sediment by the end of the Jurassic. Since then, the overlying sediment has been removed by erosion.

The combination of tectonic compression and crustal extension left the limestone peppered with faults and fractures, which gave access to water and localised dissolution that created numerous channels and voids within the limestone. The ingress of water — possibly from an ephemeral shallow sea that persisted in the region that eventually became Ireland — also dolomitised the limestone along the faults and joints during the mid- to late Carboniferous (https://www.researchgate.net/figure/a-Schematic-palaeogeography-across-the-North-Wales-Platform-and-b-stratigraphic-log_fig1_286489209). Finally, copper mineralisation of the dolomitised limestone faults and voids is believed to have occurred in the Permo-Triassic periods.

(However, burial beneath *c.* 1 km of sediment, which would mean a temperature of only *c.* 50˚C would be too cold for hydrothermal mineralisation of copper. Porphyry copper precipitation and deposition requires temperatures between 200˚C and 800˚C, usually associated with igneous activity several kilometres beneath the deposits. So, not only is the source of hydrothermal fluids unconfirmed, but the heat source is also entirely unknown, and therefore assumed to have been magmatic, as there is no evidence of concurrent igneous activity.)

Great Orme copper mines

The Great Orme copper is described in various sources the result of a series of diagenetic, epigenetic, meteoric, supergene mineralisation processes. Diagenesis is the process of physical and chemical changes after sedimentation, and frequently is caused by water–rock interactions. Epigenetic is the geological processes that occurs at or near the Earth's surface. Meteoric means rain water and other precipitation, and melting glaciers. Supergene (as opposed to hypogene) is the process of metal enrichment that, occurs relatively near the surface by oxidation and other chemical weathering reactions (Fig. 36, *opposite*).

Descending meteoric waters oxidise the copper ores, which originally were mainly chalcopyrite ($CuFeS_2$) and other copper sulphide minerals. Supergene enrichment occurs following the leaching out of other elements, in this case iron and sulphur, which are transported downward by percolating groundwater, and which may have reacted with other substances at the deeper supergene–hypogene boundary forming secondary deposits. Such chemical reactions (in the case of malachite) can take place at near atmospheric pressure and temperature.

As with most chemical processes, the rate of reaction can double with every 10˚C increase in temperature. Hence supergene enrichment occurs more rapidly in tropical climates with high

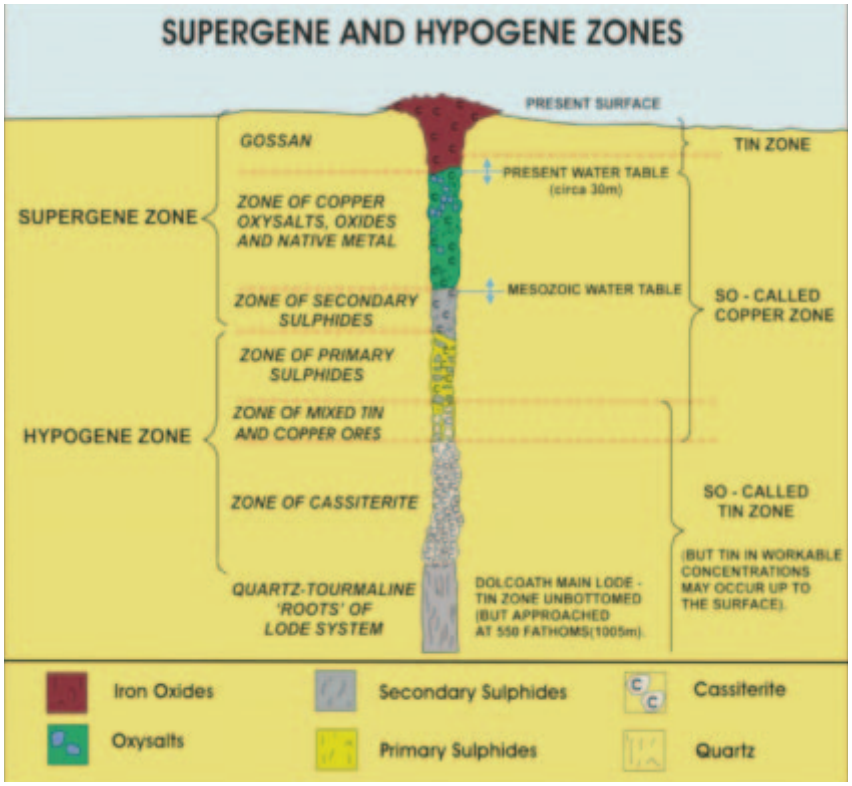


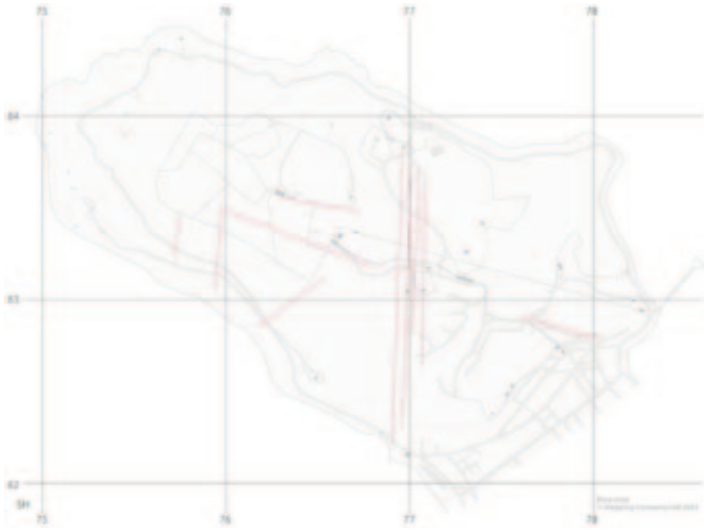
Figure 36 Schematic showing mineralisation associated with supergene and hypogene zones (example shows the Cornish sequence; http://projects.exeter.ac.uk/geomincentre/min6.htm).

rainfall. Wales experienced just such a climate during most of the Tertiary Period. Chalcopyrite is presumably chemically converted to Malachite ($Cu_2CO_3(OH)_2 + O_2$) by reaction with the limestone to form the carbonates and hydroxides.

(The Trodos Mountains in Cyprus, the main sources of Mediterranean copper in the Bronze Age, is another example of such tectonic and spreading ocean ridge features associated with mineralisation and enrichment.)

Figure 34 Shows the Great Orme copper mine entrance at ground level. Figure 37. shows a schematic map of the Great Orme copper veins worked by Bronze Age and later miners.

Figure 37 The Great Orme copper mines: schematic map showing location and orientation of the copper ore veins (http://www.goes.org.uk/html/base_map_with_lodes.html).



Mining continued through Iron Age and Roman times, and an estimated 2000 tonnes of copper was extracted, leaving *c.* 113 km (70 miles) of subterranean tunnels extending to a depth of 70 m. Some of the workings are so narrow that it is thought they were excavated by women and /or children.

The first metal tools were made of pure copper. Bronze artefacts, probably originally made accidentally during copper smelting, are an alloy of copper and tin or arsenic. The earliest bronze artefacts are dated *c.* 7000 years ago, made by the Vinča people in what is now the Balkans (https://emerging-europe.com/after-hours/how-vinca-culture-changed-the-way-we-think-about-the-stone-age/).

One of oldest known, and now iconic Bronze Age men, was discovered in 1991, when a well-preserved body was found by skiers in a melting glacier in the Ötztal Alps between Austria and Italy (Fig. 38). Named 'Ötzi' his body had been dated between 5400 and 5100 years old. The archaeological evidence suggests that he was murdered, as his body had an arrowhead that had entered from behind. He carried with him a knapped chert knife, the means to make fire and a high-quality copper axe. Presumably these artefacts were left with the body because, if taken, his assailants would have had difficulty keeping their complicity in his murder a secret.

Figure 38 'Ötzi' as he was discovered and a reconstruction of him and his copper axe (https://www.pri.org/stories/2017-04-06/ and https://www.earthdate.org/node/92).

Figure 39 Lake Constance Bronze Age lake village.

Figure 40 The Nebra Sky Disc.

Ötzi's fate seems to typify the perils of living in the Bronze Age, for although many farming implements and utensils were made from bronze, ancient weapons such as arrowheads and spearheads are found in far greater numbers. As in the Neolithic, there were long-distance trading connections throughout Europe, including sea trade routes, attested by the Dover Bronze Age Boat discovered in Kent in 1992 and by the ancient Phoenician word for the British Isles, 'Cassiterides', meaning 'of tin' *(see below)*. Snapshots of Bronze Age life are given by settlements such as the Lake Constance central European Bronze Age village (Fig. 39), and the Must Farm and Flag Fen village sites, both near Peterborough. The dwellings at the Lake Constance village are built on stilts partly to give easy / safe access for boat launching and also for defensive reasons.

One of the most interesting and potentially the most significant Bronze Age finds was the Nebra Sky Disc (Fig. 40). Made of bronze and embellished with gold discs and other shapes, it measures *c.* 300 mm in diameter. It is said to depict the constellation of Pleiades in conjunction with other heavenly bodies and facilitated the predication of certain annual astronomical events, possibly relating to the cycle of the agricultural year. Analysis revealed that the copper was sourced in the Alps, the tin was from Cornwall and the gold possibly from England and Ireland.

The Nebra Sky Disc's discovery in 1999 caused a stir when it was found in Saxony alongside other high-status Bronze Age artefacts, all dated *c.* 3800 years old. More recently, however, it has been suggested that the disc was simply 'stashed' with these other, allegedly 'looted', items and was more likely to be 1000 years younger (thus, of Iron Age date).

Relative hardness of metals

Pure copper implements, in many ways, must have been more of a novelty or ceremonial item rather than a technological improvement over bone and stone tools. Certainly, copper could never be made razor sharp like flint; and despite being tough and virtually unbreakable, a copper axe or knife would not hold its edge very long. On the Vickers scale of hardness, annealed copper is relatively soft at *c.* 40 Vickers, and thus can be worked cold to a value approaching *c.* 95. In comparison, soft wrought iron is also *c.* 95 Vickers, but most structural steels are between 150 and 200 Vickers. With the addition of more carbon (up to 1%) and other trace elements (Cr, V, B) tool steels can be hardened to over 650 Vickers.

Pure tin is 50 to 75 Vickers, but when alloyed with copper, a 10% tin bronze will have a hardness of *c.* 100 Vickers, but with the added disadvantage that it is brittle. This is a universal problem with all materials (especially metals), that when made stronger by hardening, they become more brittle. Reducing the tin content of bronze to 5% reduces the hardness to *c.* 75 Vickers, but renders it sufficiently malleable to be able to be beaten into thin sheets that can be fashioned into plates, vessels, body armour and helmets.

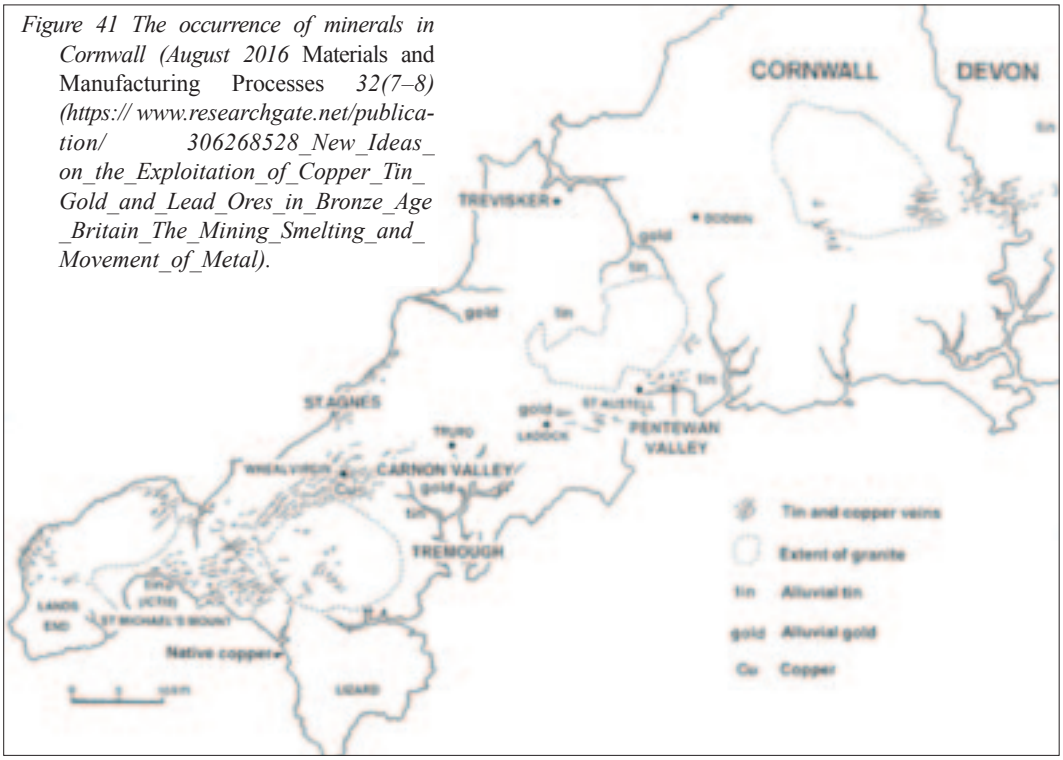


Figure 41 The occurrence of minerals in Cornwall (August 2016 Materials and Manufacturing Processes *32(7–8) (https:// www.researchgate.net/publication/ 306268528_New_Ideas_on_the_Exploitation_of_Copper_Tin_Gold_and_Lead_Ores_in_Bronze_Age_Britain_The_Mining_Smelting_and_Movement_of_Metal).*

Ancient tin sources

The major tin deposits in Cornwall (Fig. 41), like the copper deposits in Wales, are present as a direct result of the effects of the Variscan Orogeny, which also caused major deformation and uplift in south-west England. What is now the 'country rock' in Cornwall, was originally also deposited in the Rheic Ocean, but in deep water and very much earlier than the Welsh carbonate platforms.

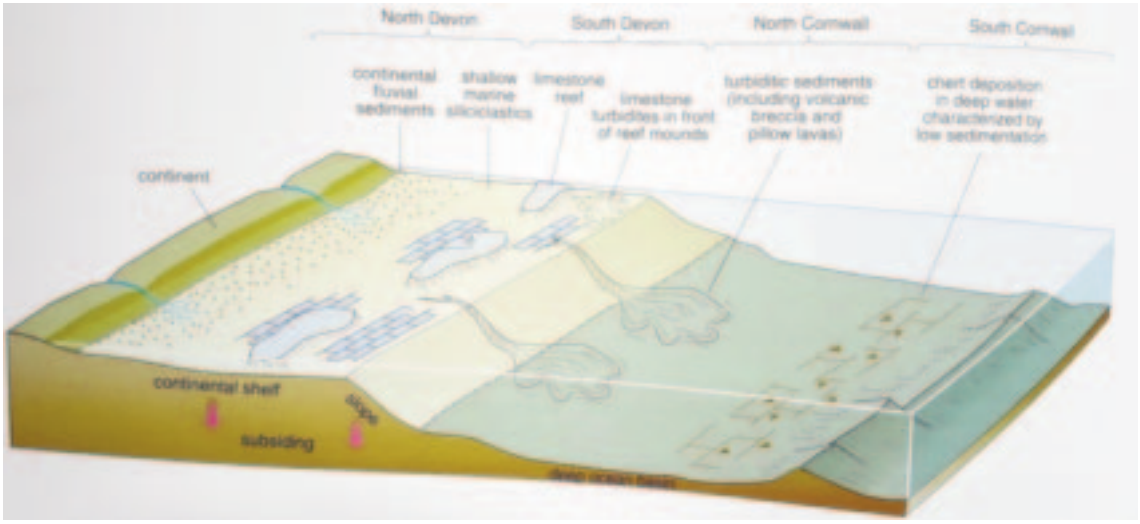


Figure 42 Devonian and Carboniferous depositional environments across south-west England, prograding from the edge of a continental land mass in north Devon into the deep Rheic Ocean Basin (OU SXR 269, fig. 9.2; © The Open University).

Figure 42 shows Cornwall's Devonian mudstone and shale deposits, which were later metamorphosed into slate following the emplacement of the Cornubian granite batholiths, *c.* 290 Ma. Weathering and glacial erosion eventually resulted in exposure of the subterranean batholiths, which now nestle in the roots of what was once a great Palaeozoic mountain range.

As in Wales, Cornish tin (together with copper, lead, tungsten, zinc and other minerals) was deposited by hydrothermal processes, but in south-west England there was no doubt about the heat source. At an average of 60 ppm, copper is the 26th most abundant element in the Earth's crust, whereas tin is substantially rarer at 2.3ppm and 49th. Within sea water and hydrothermal fluids, metallic elements are present only in ppb or even ppt levels, hence it takes an extraordinary length of time to precipitate and concentrate sufficient metal to make an economical deposit. Tin within a hydrothermal fluid is transported most commonly as a chloride ion (SnCl- or SnCl2), and at 700°C water can accommodate *c.* 100 ppm Sn, which comes out of solution (and is later oxidised) at 300–500°C, usually at significant depth. Synonymous with the fractional distillation of crude oil on a modern chemical plant, hydrothermal fluids carry a variety of metallic ions, all of which precipitate out of solution at a preferred temperature and pressure, hence the concentration of certain metals in certain zones within the crust.

Cassiterite is one of the last ores to precipitate out of a hydrothermal fluid, and forms high concentrations of tin in the upper reaches of the veins. This was fortunate for Bronze Age Britons because once exposed by erosion, the local rivers of Cornwall became 'festooned' with tin nuggets and placer deposits (natural accumulations of heavy minerals within particulates moved by water, wind and/or gravity). Being such high-grade ore, it was easy to find and to pan, because it weighed so much more than most of the other non-descript pebbles in the river. Doubtless, Bronze Age Britons panning for tin also found a fair share of gold in this region.

Big yellow axes

The advent of the bronze axe greatly increased the effectiveness by which ancient Britons could clear woodland for agriculture. The population of England *c.* 4200 years ago has been estimated at *c.* 250 000. By this time deforestation was already progressing at an accelerated rate. Woodland had colonised Britain from the end of the Ice Age and reached equilibrium between 7000 and 5000 years ago when the coverage was *c.* 75% (https://www.forestresearch.gov.uk/documents/1437/QJF_legacy_of_fragmentation_may06.pdf). By the onset of the Iron Age, it is estimated the coverage had been reduced to *c.* 50% coverage, and then to only 15% by 1215, as recorded in census records. And much later, the North Yorkshire moors were almost completely deforested to support the alum shale industry, which required bonfires to be kept alight for days on end.

Smelting copper and tin

Except for gold, metallic elements exist in the Earth's crust as sulphides, oxides or carbonate ores. So, despite the word 'smelt' being derived from the Germanic language verb meaning to melt, smelting is the process by which chemical reactions remove unwanted oxygen, carbon and/or sulphur, at a temperature that is either higher or lower that the melting point of the parent metallic element, depending on how much energy is required to remove the unwanted elements.

Tin ore (cassiterite) is an oxide (Sn_2), hence the metallic component can be extracted by simply heating it in a reducing atmosphere, for example in a charcoal fire. In such an environment the carbon in the charcoal bonds with the oxygen in the ore to form carbon dioxide, which liberates the tin (So,$SnO_2 + C \rightarrow Sn + CO_2$). Malachite is a copper carbonate hydroxide ($Cu_2CO_3(OH)_2$) and as such requires a two-stage conversion process whereby first the ore is oxidised to form CuO, after which the CuO is reduced to form elemental copper.

So, in the presence of hot air (oxygen) $Cu_2CO_3(OH)_2 + O_2 \rightarrow 2CuO + H_2O + 2(CO_2)$ (the CO_2 and water vapour are lost to atmosphere as gasses).

Continuing to heat, but in a reducing atmosphere, the remaining copper oxide reacts with carbon and 'reduces' to copper, i.e. $2CuO + C \rightarrow 2Cu + CO$ (and as above, the carbon monoxide is lost to atmosphere).

The chemistry behind the smelting of copper and tin ores is, to us, a relatively simple process ,but obviously Bronze Age people knew nothing of redox reactions. Nevertheless, they became

proficient foundry workers. One is left wondering, maybe, how did ancient people first stumble upon the combined mechanisms of oxidation and reduction? As luck would have it, it is possible to smelt copper from malachite simply by 'roasting it' in the heart of a fire. When a mixture of crushed malachite and charcoal is roasted on a fire, there is, initially, enough air present to oxidise the ore to CuO, whereafter, when the oxygen in the fire has been consumed, the atmosphere becomes reducing.

Figure 43 Home-made smelting kit: crushed malachite and charcoal, a small stainless steel crucible and welding gloves.

Making my own bronze arrowhead

I took it upon myself to manufacture a bronze arrowhead from scratch using some malachite and Cornish cassiterite from my own collection — substantially assisted by modern technology. I was 'reliably' informed by various You Tube videos that in the early Bronze Age smelting would have been undertaken in a ground-level fire pit, probably on a relatively small scale, and using some sort of animal skin bag as a bellows to force air through a hole in the side of the pit. I say 'small scale' because it is necessary to start with a certain ratio of ore/coke to air. Otherwise there is a risk of incomplete copper recovery if the available oxygen runs out before it has oxidised all the ore.

Another reason for believing it was a small-scale operation is that no evidence has been found of large-scale Bronze Age forges or furnaces. The batches of copper appear to have been smelted in small earthenware pots packed with crushed ore and charcoal, which could be added to, and later removed from, fire — thus enabling copper production to continue so long as the fire remained lit.

Figure 43 shows my prepared materials, and on this occasion, with no attempt made to take account of the optimum ratio of charcoal to ore (which I later learned was 3:1 ore to charcoal by weight). Not having anywhere convenient to excavate a fire pit, nor any earthenware pots, I took advantage of modern technology and used a stainless steel crucible and the wood-burning stove in my lounge. Figure 44 shows the crucible (containing the crushed ore and charcoal) nestling among the hot coals, where it remained — hopefully oxidising — for 20 minutes before I buried the crucible in fresh charcoal to create a reducing atmosphere for the

Figure 44 A green flame hovering above the stainless steel crucible, suggesting oxidation is in progress.

second phase of the conversion process. Believing my dual fuel stove to be hotter than any Bronze Age fire pit, I removed the crucible after a further 20 minutes, quenched it in water and tipped the contents into a kitchen sieve (Fig. 45).

Voilà, a mixture of partially burnt charcoal and something that was most definitely copper-coloured, though my initial euphoria soon turned to dismay when I picked out the copper-coloured 'blocky' material only to find it was similar in weight and density to the charcoal.

The various You Tube videos I had watched depicted individuals gleefully pouring molten copper from their crucibles whereafter they 'panned' the remnant sludge to remove any smaller metallic particles. My black and copper sludge was more or less of uniform density, which made it impossible to separate by panning, causing me to spend an hour or so peering down a stereo microscope with a pair of tweezers.

Figure 45 The crucible contents after smelting.

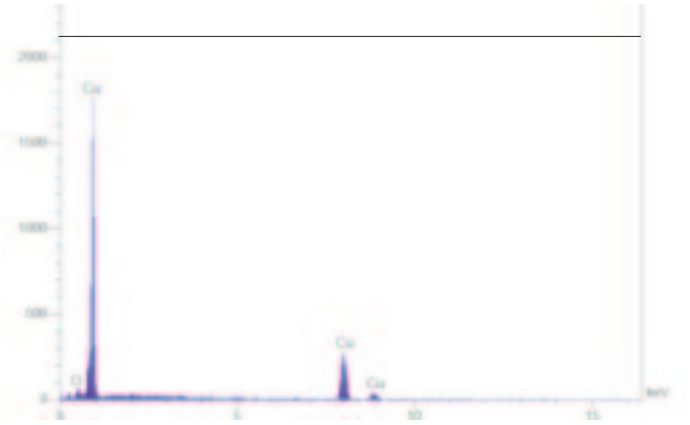


Figure 46 Three copper blocks mounted on a 10 mm diameter adhesive carbon stub.

What was it that I had made?

At work early the next morning I fired up the scanning electron microscope.

Figure 46 shows three of the millimetre-sized coppery blocks mounted on a 10 mm diameter carbon stub in preparation for elemental analysis, the results of which (the inset image) revealed the blocks were indeed 100% copper. Clearly, I *had* managed to smelt the copper without exceeding its melting point. Result!

Closer examination of the copper blocks (Fig. 47) revealed that the reason for their low density was their sponge-like and dendritic morphology, so perhaps I had approached the melting point after all — which for copper is 1085°C.

I later repeated the process, but this time used a larger volume crucible and with oxidation and reduction 'furnace soak times' of *c*. 40 minutes each time. Increasing the furnace time resulted in the production of some molten copper, but with a yield nowhere near as high as with the first crucible. I also managed to burn through the stainless steel crucible in the process!

The copper metal I produced did not 'pool' in the bottom of the crucible as anticipated, but rather formed as discrete millimetre and sub-millimetre spheres (Fig. 48). Closer examination of an individual copper sphere revealed a surface that appeared to consist of thousands of micro-spheres, for reasons unknown (Fig. 49).

Figure 47 SEM image of the copper blocks revealing a sponge-like and dendritic structure.

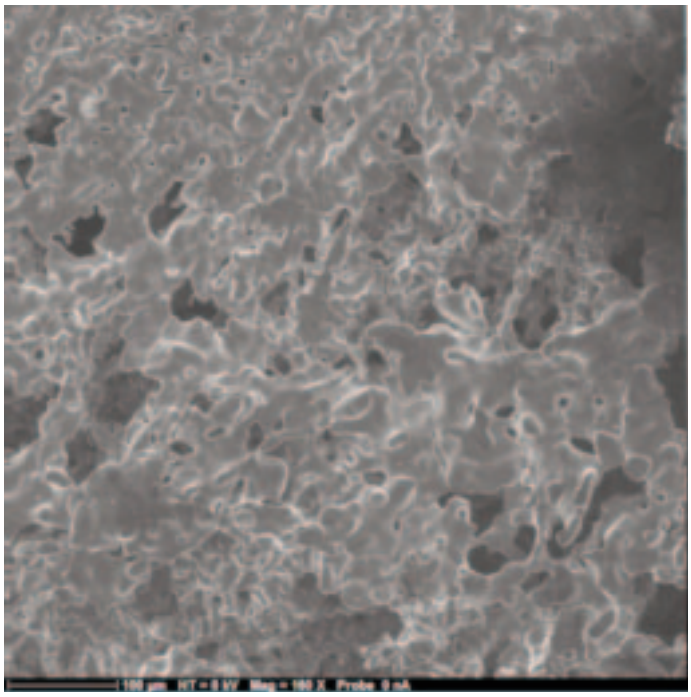


Figure 48 Examples of the copper spheres produced from the second smelting trial.

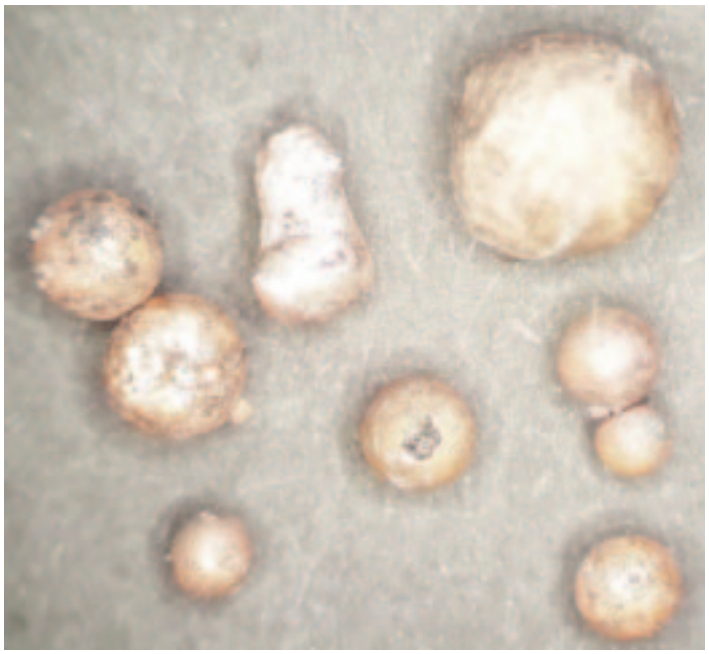
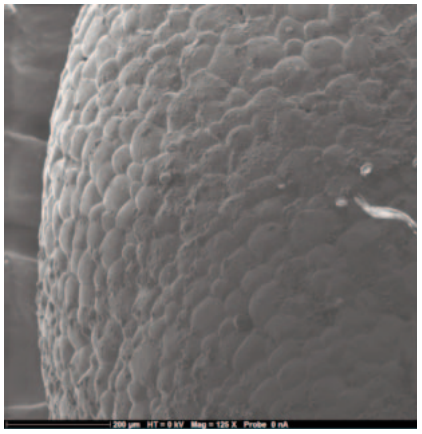


Figure 49 The mysterious topography of an individual Cu sphere.



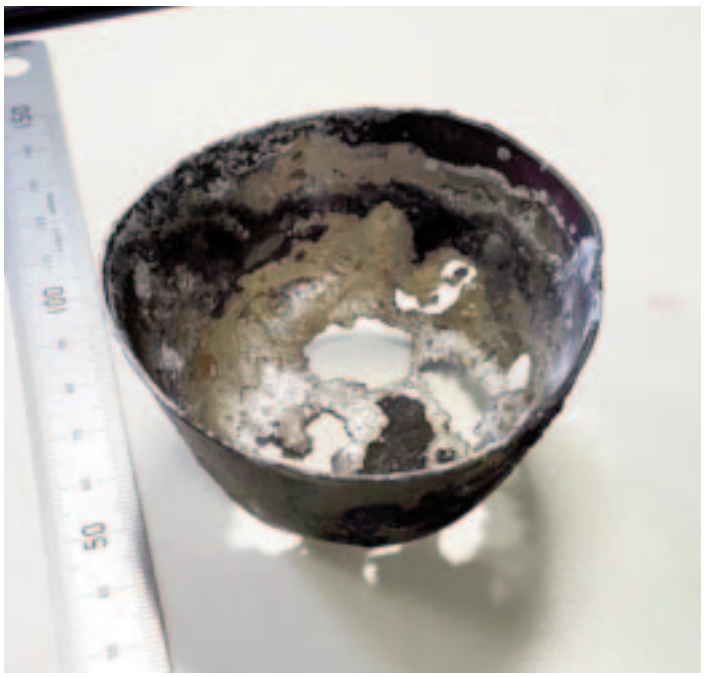


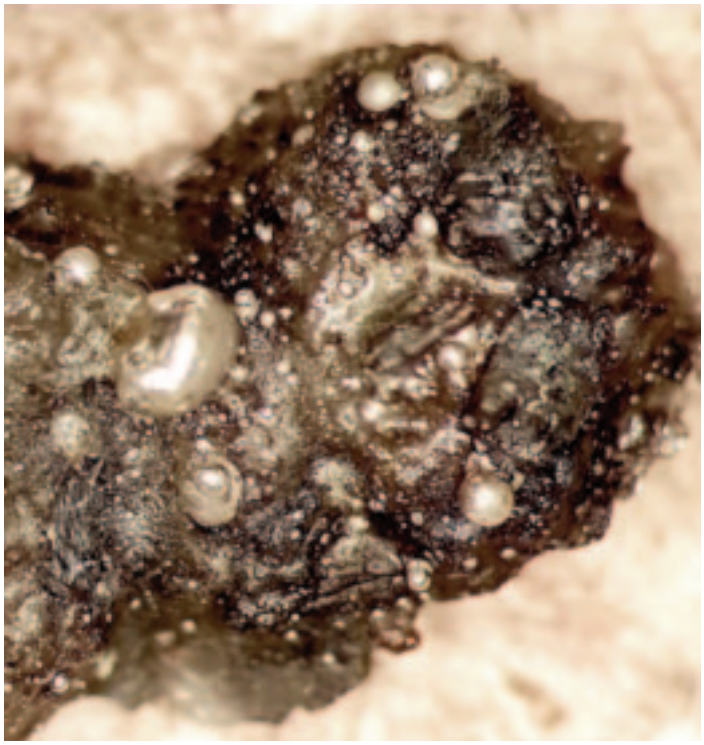
Figure 50 The remains of my steel crucible.

Spurred on by my success with the malachite, I prepared a cassiterite sample in the same way.

Despite having a lower melting point than copper (220°C), I was advised (You Tube again) that tin smelting requires a temperature of *c.* 1200°C — significantly higher than the melting point of both tin and copper separately, and also bordering on the upper temperature limit of a charcoal fire.

My one remaining crucible was a plain carbon steel item, which I thought might actually be a better prospect than stainless steel, as it has a higher melting point: 1538°C for steel [iron] compared to 1400°C for stainless steel. Not having to concern myself this time about the oxidation reaction, I placed the crucible of crushed ore and charcoal in the centre of the fire — my log burning stove again — and immediately buried it in charcoal. Leaving the door of the stove slightly ajar to better fan the flames, the temperature rapidly climbed to a level where it was uncomfortable to be in such close proximity and almost too bright to look at directly. Realising that soon I would need to fully open the 'furnace' door and reach inside with a gloved hand to extract the crucible, I fashioned a rudimentary aluminium foil balaclava to protect my face.

Figure 51 A charcoal fragment festooned with sub-millimetre and microscopic tin balls.



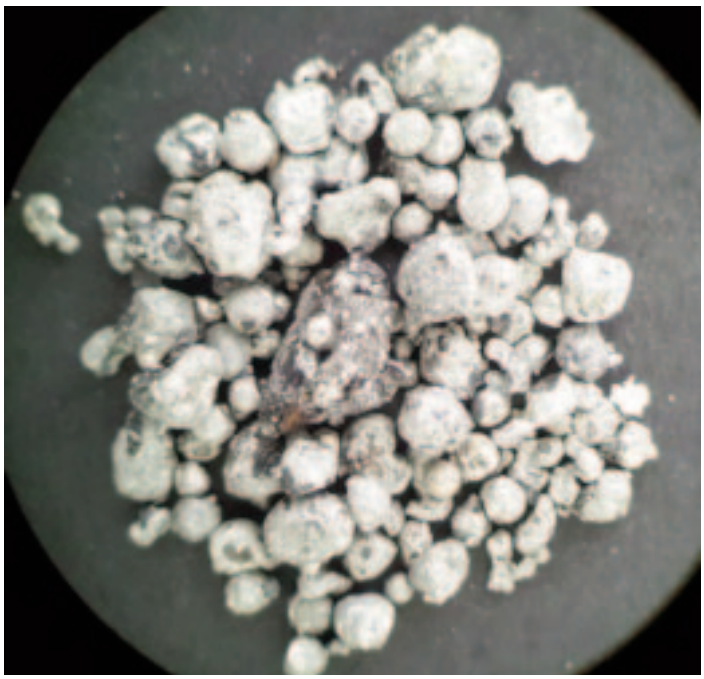


Figure 52 The results of my tin smelting endeavours: a collection of somewhat battered mm-sized tin balls.

After a 50-minute soak at maximum temperature I began to pick off the overlying charcoal embers with metal tongs to expose the crucible beneath, only to witness molten metal dripping through a hole in the base. I managed to recover what was left of the crucible (Fig. 50) to a safe area by the stove and, the next morning, collected the escaped metal from the stove's ash tray, which thankfully *did* turn out to be tin, and not some unwanted tin-iron alloy. Fortunately, the bottom of the crucible had not fallen out completely and it still contained most of the charcoal residue, which, to my surprise was literally festooned with sub-millimetre spheres of tin (Fig. 51). Each tiny point of light in the photo is an individual ball of tin.

There were also numerous loose spheres in the mix, but probably 90% were bound up within the charcoal residue, which I had to crush quite violently with a hammer to release. Still, the smallest of the entrapped microspheres refused to budge, making the residue again impossible to segregate by panning, tin infested charcoal being relatively heavy. After spending another hour with tweezers and the stereo microscope I was able to collect the fruits of my labours (Fig. 52).

I now have the greatest respect and admiration for Bronze Age smelters.

Armed now with the necessary raw materials I began to turn my attention to how I might cast my own bronze arrowhead — but before that, I needed to do some more chemical calculations.

Figure 53 Red: the 'master' tool, fashioned from left-over DIY materials; green: a wax casting from the master tool.

Figure 54 Low-temperature wax replica.

Calculating smelting temperatures

It seems counter intuitive that the smelting temperature of an ore can be significantly higher *or* lower than the melting point of the extracted metallic element. The melting points of copper and tin are 1038°C and 220°C, respectively. Having performed the calculations I can reliably confirm that the minimum smelting temperature for tin is *c.* 640°C — so, very much higher than its melting point.

Regarding the minimum smelting temperature of copper I can inform you, less reliably from my own calculations, that malachite oxidises to copper oxide at a minimum temperature of 670°C, and that afterwards the copper oxide begins to reduce to elemental copper at 905°C. These temperatures are consistent with my experimental experience, as described above, in that most of the copper I produced from the first small batch was a sponge-like substance of low density that had not quite melted. Smelting temperatures vary, but practitioners who know what they are doing (myself not included), use higher temperatures to increase the reaction and conversion rate, and with the aim being to produce molten metal.

My own calculations were based on the equation:

$\Delta G = \Delta H - T\Delta S$

Where ΔG is the Gibb's free energy value; 'H' and 'S' are, respectively, enthalpy and entropy — values for which are published and may simply be 'looked up'.

Enthalpy in this context is the amount of available heat energy in joules.

(I would be happy to send details of my calculations to anyone interested: sbc-secretary@outlook.com.)

Bronze arrowhead manufacture

During the Bronze Age, bronze items were cast using carved stone and fired-clay moulds and, as techniques became more sophisticated, coring and lost-wax casting to produce hollow sections (www.researchgate.net/publication/320231028_Reconstruction_of_the_Casting_Technology_in_the_ Bronze_Age_on_the_Basis_of_Investigations_and_Visualisation_of_Casting_Moulds). Here in the Anthropocene, in Stockton-on-Tees, we favour the use of castable dental gypsum that, jeweller's wax and a 3000C oxy-propane torch.

From the 'master tool' shown in Figure 53 I made a two-part silicone mould, from which I could cast. The master tool was fashioned from a wooden dowel, two lollipop sticks and three layers of kitchen workshop laminate, then painted Humberol red to fill in the crevices between the three components and to impart a more uniform surface finish. The green carving wax melted at a relatively high temperature and was prone to retaining gas bubbles, so I switched to using a low-temperature, if more fragile moulding wax (Fig. 54).

The next stage was to cast a wax replica in gypsum, whereafter the wax is melted out over several hours in a kiln at *c.* 730°C, creating a pristine white mould (Fig. 55). The gypsum is cast around the wax replica in a metal flask. Unfortunately, gypsum moulds are prone to cracking at elevated temperature — as shown in the figure — a recurring problem that I never managed to overcome.

Figure 55 A cracked gypsum mould (outer flask removed).

Figure 56 A freshly cast, red hot arrowhead, and semi-molten residual bronze.

Figure 57 A cast arrowhead after initial wire brushing — not pretty!
Figure 58 The finished item.

Thus, my bronze arrowheads always require a good deal of manual finishing.

Figure 56 shows a freshly cast arrowhead still in its flask, which is perforated to aid drying and venting.

Figure 57 shows my relatively poor first casting, the bulb on the end being intentional. With hindsight, I should have practised more first using some scrap bronze before using my precious home-smelted material.

Figure 58 is the best side of the finished item after a great deal of hard work!

Figure 59 The five more successful cast arrowheads.

And finally, Figure 59, five of the six arrowheads I cast: from left to right, no. 1 is the first and only one made from fully home-smelted minerals; no. 2 has too much copper; no. 3 is the best one; and nos.4 and 5 are the two silver ones. As you can see, I was experiencing flask-cracking issues to the end!

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From hollow guts to nettles: my favourite fossil

Mike Grover

Introduction

My collection of fossils consists mostly of fragments, a bit like patterned gravel, but a few are more complete and one in particular is my favourite. It is not very old, it is not big, but it is complete (Fig. 1). When I found it some 40 years ago, I did not even realise that it was a fossil!

It is a coral, *Goniopora websteri,* from Bracklesham Bay, West Sussex, and I found it complete with its home of some flint pebbles. While I was photographing it, I realised that I did not know much about corals, so I did some research, and would like to share my findings; and to tell you why it is my favourite fossil.

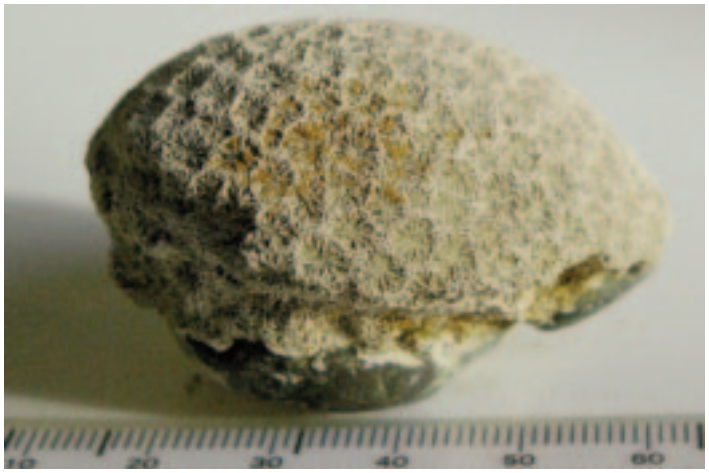


Figure 1 The author's fossil specimen of Goniopora websteri.

Coral basics

First, here are some basics about corals in general.

Corals belong to the class Anthozoa, within the phylum Cnidaria. Cnidarians (the 'c' is silent) all contain stinging cells called cnidocytes or nematoblasts, and they get their name from the modern Greek word for nettles (ending in 'knide'). The phylum used to be called Coelenterates, from the Greek for hollow (koilos) and intestine (enteron). Both names are apposite. The phylum includes anemones, corals, jellyfish and sea pens. Cnidarians usually take one of two forms: mobile medusae (like jellyfish) and stationary polyps (like corals and anemones). However, jellyfish have a polyp stage in their life cycle. Corals can reproduce asexually by budding, which is how colonies form; by fragmentation — if a bit of coral breaks away and grows somewhere else ; and sexually by producing gametes. The coral polyp — the living bit — sits in a cup-shaped structure called the calice, on top of a calcite skeleton called the corallum or the corallite (depending on different publications).Both structures are secreted by the polyp. The corallite contains vertical septa with, in modern corals, radial symmetry, for example as shown in *Montasarea cavernous* (Fig. 2).

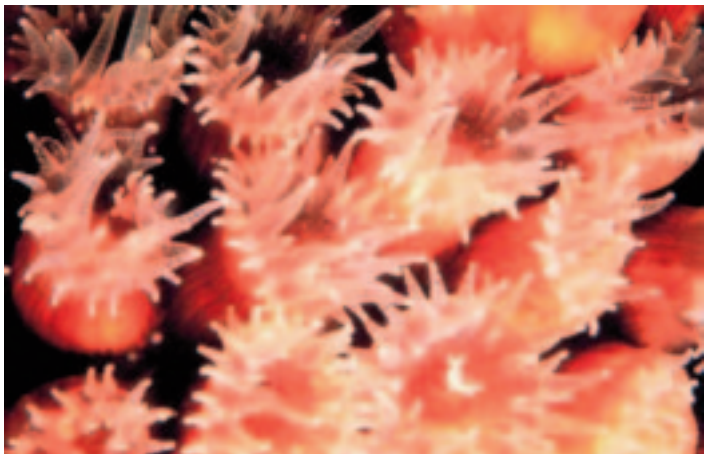


Figure 2 A living coral, Montasarea cavernous *(Public Domain).*

Cnidarians are the simplest of true multicellular animals, the Metazoans (Fig. 3). They have some specialised cells but no true tissues. In corals the cells are arranged in two layers, forming a sack with tentacles around the top, unless the coral is hanging upside down! The two layers of cells are separated by the mesoglea, a jelly-like substance similar to the jelly in jellyfish. The outer layer contains the cnidocytes, which when contacted by prey incapacitates it, and which is then fed through the mouth by the tentacles into the gut (coelenteron). The prey is digested and absorbed by the cells, then any waste is expelled through the mouth.

To grow, the coral polyp lifts slightly and secretes a new tabulum, septa and corallum wall.

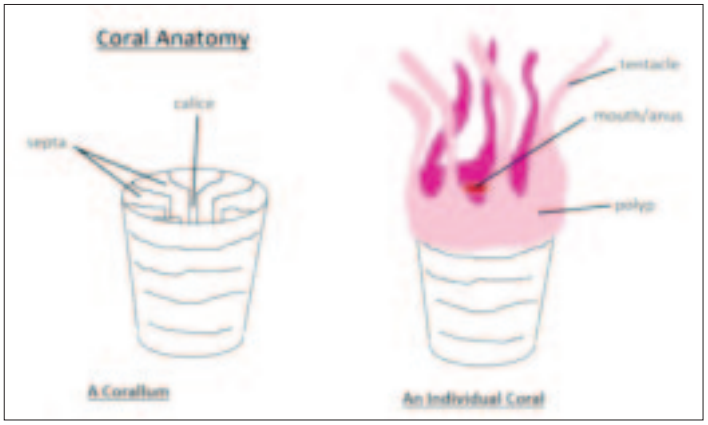
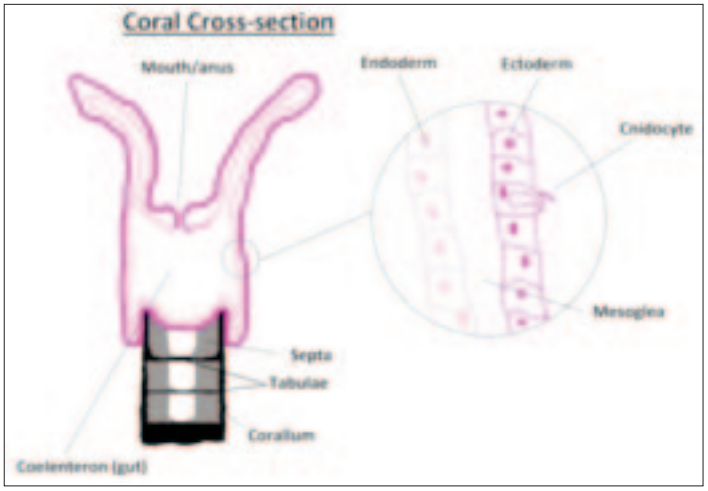


Figure 3 Basic coral anatomy: morphology and cross section (Mike Grover).



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Cnidocytes (Fig. 4) are only found naturally in Cnidarians, but there is a sea slug that eats Cnidarians and re-cycles the cnidocytes for its own defence. Cnidocytes have a coiled harpoon that is stored inside-out within the cell. There is a 'trigger' on the cell that when brushed against, or activated chemically, releases calcium ions into the cell. Water is sucked rapidly — in microseconds — by osmosis into the cell and forces the harpoon out (a bit like blowing into a used rubber glove to inflate the fingers). The harpoon is barbed and can also inject venom into the prey.

Corals are either solitary or colonial. If colonial, they share a layer of soft tissue between members of the colony. Modern corals are extensive reef builders. When a polyp dies, another polyp builds on top of the old corallum. In this way coral atolls and reefs form as sea levels rise or as the ocean floor subsides (which explains why some coral islands are surrounded by deep water).

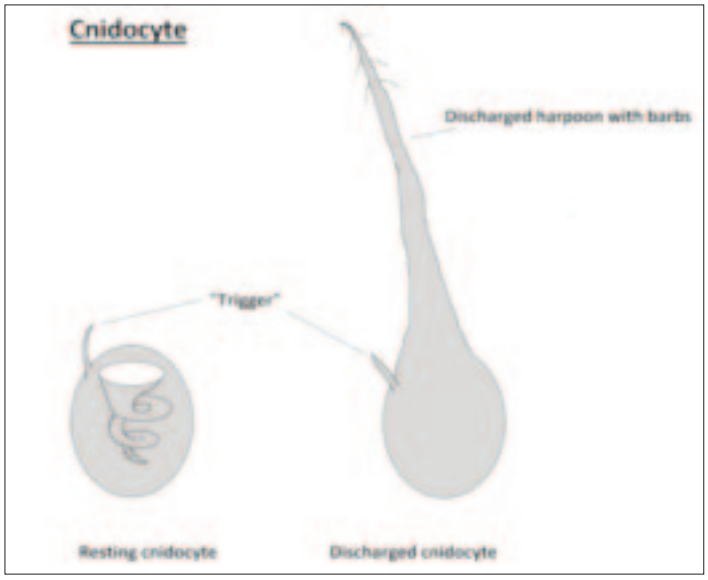


Figure 4 Drawing of a coral cnidocyte (Mike Grover).

Fossil corals

There are three major groups of corals in the fossil record: the Tabulata and Rugosa (both now extinct) and the Scleractinia (hexacorals — the modern corals). Fossil corals can be found in rocks of at least Cambrian age, but coral did not become abundant until the Ordovician, when two major groups appeared: the Tabulata and the Rugosa. These two groups expanded, but were drastically reduced by the extinction event at the end of the Devonian. The Rugosa expanded again, but both groups became extinct at the Permian extinction event (Fig. 5).

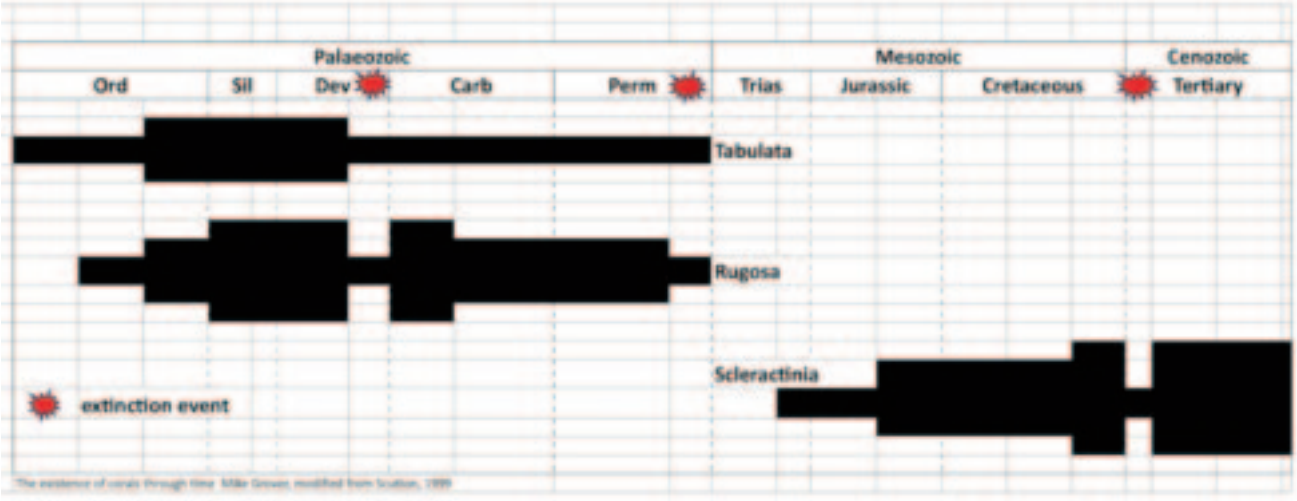
In general the appearance of both the Rugosa and the Tabulata was similar to modern corals, both as solitary and as colonial forms.

The Tabulata were all colonial, with calcite skeletons and with a huge morphological range. They appeared in the early Ordovician and are named after the extensive transverse plates (tabulae) that partition them horizontally. They have poorly developed septa. The individual 'corals' (corallites) — in the colony are generally only a few millimetres across, but the colony can be up to a few metres in size (Fig. 6).

Figure 6 This can be seen in the photo of a tabulate coral from the Carboniferous near Payson, Arizona (scale in mm).

By genus *c*. 60% of Rugosa (from the Latin for 'wrinkled') were solitary and had aragonite skeletons. They appeared later in the Ordovician than the Tabulata (*see* Fig. 5). Most of these corals, especially the solitary ones, lived on soft substrates with adaptations to cope with the amount of accumulating substrate. Horn-shaped corals rested on their sides and were adapted to a slow build-up of substrate. Straight corals were adapted to grow vertically to cope with accumulating sediment (Fig. 7, *opposite*). The Rugosa have distinct septa (Fig. 8), *opposite*.

Figure 5 The evolution of corals (after Scutton 1999).



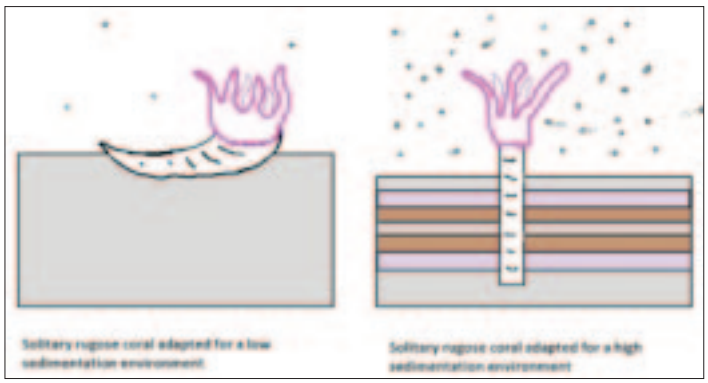

Solitary rugose coral adapted for a low sedimentation environment
Solitary rugose coral adapted for a high sedimentation environment

Figure 7 Growth forms of solitary Rugosa corals (Mike Grover).

Colonial corals were also adapted to cope with various levels of sediment deposition. Those adapted for low sediment conditions grew new corallites on the colony edge. This produced flat colonies that could spread and compete for space. Other species adapted for high sediment conditions and grew new corallites between the pre-existing corallites. This growth tended to produce taller, fan-shaped colonies that could shed sediment.

The Rugosa can be differentiated from the Scleractinia by examination of the pattern of septa. The tabulae are much less prominent. As mentioned above, modern corals have a radially symmetrical pattern of septa in cycles of six, so the septa should be in multiples of six. The Rugosa have a bilateral symmetry to their septa formation, with six septa forming initially and then further septa formed in only four of the initial sectors,

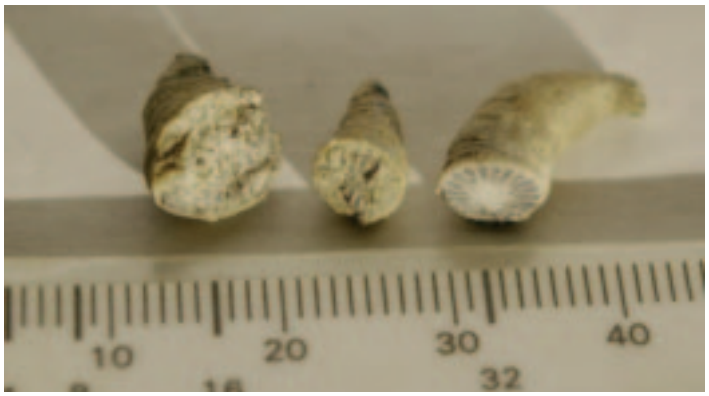
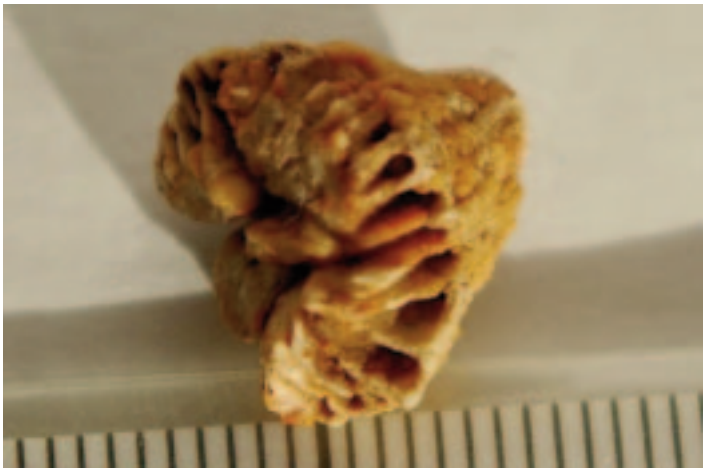


Figure 8 Carboniferous solitary Rugosa corals: (above) from near Caldbeck, Cumbria; (below) from near Payson, Arizona (scales in mm).



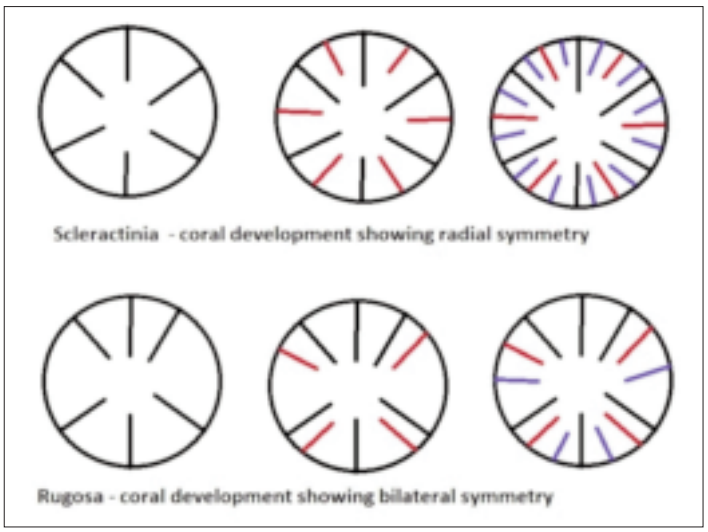


Figure 9 Diagram of solitary rugose coral septa development, showing bilateral symmetry (Mike Grover).

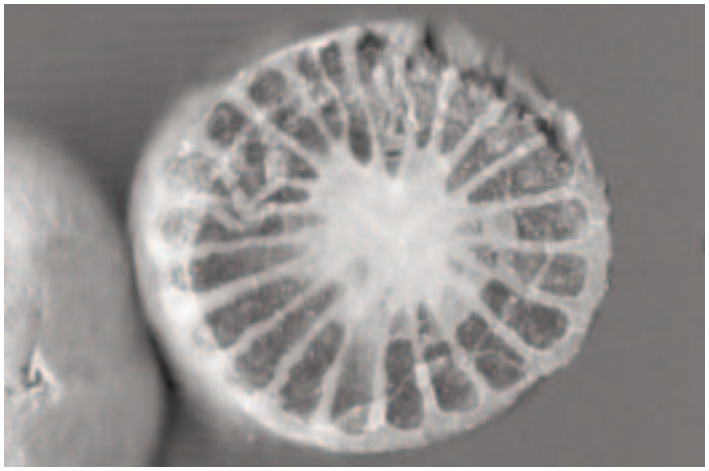
so the septa should be in multiples of four, plus six (Fig. 9). However, as these two coral groups existed at different times, identification should not be a problem — simply count the septa, if you can!

Counting the septa can be difficult, but by grinding the surface flat and then scanning the flat surface it is easier to count them on a printed paper (Fig. 10).

Modern corals

Modern corals belonging to the Scleractinia appeared in the later Triassic, and probably did not descend from either the Rugosa or the Tabulata (*see* Fig. 5). The Scleractinia were reduced by the extinction event at the end of the Cretaceous, but expanded afterwards. They were, and still are, particularly good at building reefs and are generally found, as were the Tabulate and Rugosa, at mid to low latitudes in shallow water up to *c.* 30 m deep. The corallites are composed of aragonite. Most require warm, clear, shallow water, primarily because they have symbiotic algae within their 'tissues' requiring sunlight for photosynthesis. The algae provide regular energy to the coral, which it can supplement with prey captured by the cnidocytes. Palaeomagnetic evidence of fossil corals shows that many lived in similar conditions, suggesting that they also had a symbiotic association with algae.

Figure 10 Ground flat surface of a rugose coral, showing the septa clearly.



My favourite coral

The reason that my *Goniopora websteri* fossil is my favourite is because it tells a story in geological terms — a long story (Fig. 11).

It starts sometime between 65 and 145 million years ago in Cretaceous seas teeming with sponges living on the carbonate ooze. The sponges died and the silica spicules they contained dissolved as the chalk was compressed. The silica was deposited as flint in burrows and fissures in the chalk. In the Eocene, *c.* 40 Ma, there was a shallow sea surrounded to the west and south by chalk uplands. Rivers draining into this sea carried flint eroded from the chalk. As the flints crashed together, at first in the rivers and then on the seashore, they slowly eroded to form pebbles. As sea levels changed the flint pebbles rested on the floor of the shallow sea, where they were colonised by corals.

This ancient sea contained fish, including sharks and rays, bivalves and gastropods together with *Nummulites laevigatus*, a species of large (15 mm) foraminifera that lived symbiotically with algae in a similar way to coral polyps. Their presence suggests warm, clear, shallow water. The remains of the corals and other organisms were subsequently buried by silts and sands. Later, geological folding of these sediments subjected the beds to erosion, eventually being exposed on the beach at Bracklesham Bay, west Sussex, where I found my fossil.

Figure 11 Close-up photograph of the author's Goniopora websteri*, showing the details of its septa.*

Corals under threat

Modern reefs are the largest structures built by living organisms, but they grow slowly and are limited by their environmental requirements for clear, nutrient poor water. They are easily damaged and currently under threat. It is thought that *c.* 20% of the world's reefs are, in effect, dead. There is a delicate balance between the coral growth versus storms and grazing. The threats to corals reefs have increased in modern times with removal of coral by humans and an increase in turbid nutrient-rich water. The turbidity and nutrients are from farming run-off, soil erosion and sewage from local tourist developments. Global warming resulting in increased sea temperatures can cause the coral polyps to reject their symbiotic algae, which results in bleaching. In the short term, bleaching is reversible; but if prolonged, the coral polyps die. The rise in global sea temperature may also increase disease levels in the coral, compounding the problem.

So, here is hoping the current corals do not get fossilised prematurely!

References

Black, R. M. 1988 T*he Elements of Palaentology* (2nd edn). Cambridge UP

Dawkins, R. 2005 *The Ancestor's Tale.* London: Orion Books

Open University 2001 S193 'Fossils and the History of Life'. Milton Keynes

Scutton ,C. 1999 'Palaeozoic corals: their evolution and palaeoecology'. *Geol Today*, Sept-Oct 1999. Oxford: Blackwell Science

Bone, David 2016 *The Geology and Fossils of Bracklesham and Selsey*. West Sussex: Limanda Publishing

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The global impact of a slowdown of Antarctic Bottom Water

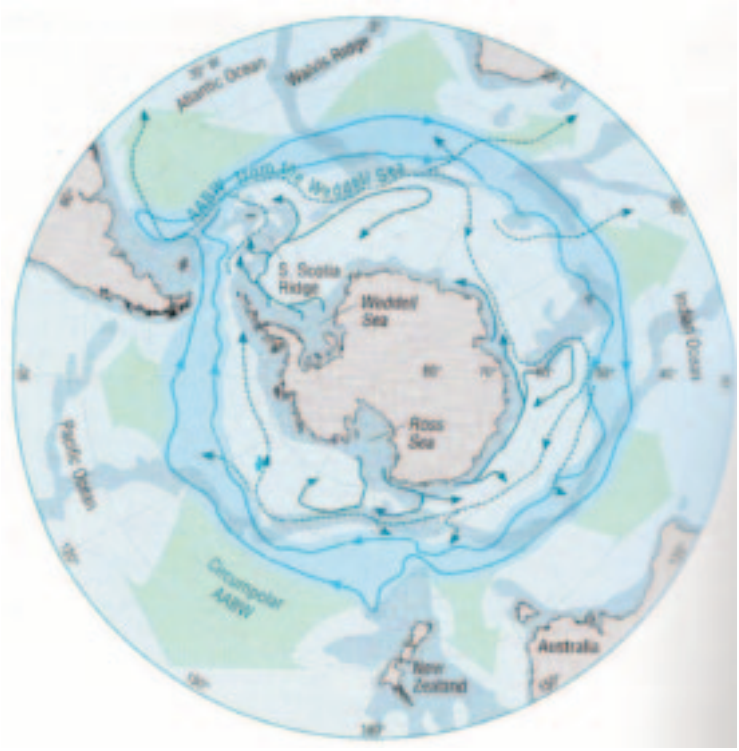
Susan Graham

Introduction

This article follows on from the article 'Ice and oceans: a look under Antarctic ice shelves' in Volume 7 of the *Proceedings of the OUGS*, and examines the implications of a reduction in Antarctic Bottom Water (AABW) resulting from ice shelf basal melting, for global climate, sea level rise and marine biogeochemistry.

To briefly recap, many Antarctic ice shelves are undergoing basal melting several hundred metres below sea level, due to a relatively warm water mass in the Antarctic Circumpolar Current accessing the continental shelf and entering ice shelf cavities. This has two extremely deleterious consequences. First, since ice shelves buttress the ice sheet, their thinning hastens the flow of Antarctic glaciers into the Southern Ocean, as we are seeing with the now famous Thwaites 'Doomsday' Glacier, recently in the news. Second, ice shelf meltwater freshens the ocean, impeding the formation of Dense Shelf Water, which cascades down the continental slope in narrow plumes (< 400 m) into the abyssal ocean as Antarctic Bottom Water (AABW). A decline in AABW formation and therefore its export to the Atlantic, Pacific and Indian Oceans, has far-reaching global impacts.

Figure 1 Flow paths of AABW to the three major ocean basins. Dark blue arrows show the densest varieties of AABW, originating from the Weddell Sea and the Ross Sea. Broken arrows show AABW formed in the Weddell Sea, flowing north in the western Atlantic and the Indian Ocean. Thick blue-green arrows indicate less dense AABW formed from Antarctic Circumpolar Deep Water, flowing equator-ward at depth from the northern edge of the Antarctic Circumpolar Current. Grey shading indicates water depths less than 3000 m (© The Open University. Colling, A. 2001 S330 Ocean Circulation*. Milton Keynes: The Open University, Chapter 6: 'Global fluxes and the deep circulation', fig. 6.25)*



Antarctic Bottom Water and global Meridional Overturning Circulation

AABW is mostly found at depths of more than 3000 m and is the most voluminous, densest water mass in the global ocean, with potential temperature colder than 0˚C and neutral density (γn) > 28.27 kg m^3 (Purkey *et al.* 2019). It is transported from the Southern Ocean in the lower limb of the Meridional Overturning Circulation (MOC) northward to the Pacific, Atlantic and Indian Ocean basins; therefore the strength of global ocean circulation can be inferred from changes in AABW export (Fig. 1). Monitoring of Southern Ocean water mass properties indicate a decline in AABW volume around Antarctica in the last three decades, reaching all three ocean basins (Purkey *et al.* 2018). Global MOC is influenced by two AABW overturning cells: the AABW cell formed adjacent to Antarctica near 65˚S (the densest variety) and the abyssal cell controlled by the northward flow of water below *c.* 3500 m, centred near 30˚S. The AABW cell is formed by Dense Shelf Water convection on the continental shelf and the latter by open ocean convection, mostly in the Weddell Sea. Convection occurs predominantly over the shelf and the densest variety of bottom water is formed there (Lago and England 2019).

Lago and England (2019) modelled multi-centennial impacts of Antarctic meltwater input estimated from drifting icebergs and ice shelf basal melt on global ocean circulation. Table 1 shows the Merino-Depoorter freshwater pattern used, which combines the basal melt estimates from Depoorter *et al.* (2013) with iceberg melt estimates from Merino *et al.* (2016), without distinguishing between the two meltwater sources. Freshwater is added at the convection sites. Three freshwater perturbation experiments were conducted (referred to as FW 2.6, FW 4.5 and FW 8.5) in which freshwater anomalies were added at a rate according to projections under RCP2.6, RCP4.5 and RCP8.5 IPCC scenarios between the years 2000 and 2200. The AABW cell was found to nearly collapse and the abyssal cell to be significantly reduced by 2100 in

Table 1 Meridional overturning strength (Sv) for the AABW cell and abyssal cell for the meltwater perturbation experiments using the Merino-Depoorter (MD) freshwater patterns. Values in parenthesis indicate the percentage decline relative to 2000 (adapted from Lago and England 2019).

		FW 2.6	FW 4.5	FW 8.5
Year	Ctl	MD	MD	MD
2050	8.4 (0)	7.3 (13)	2.8 (66)	0.9 (89)
2100	8.4 (0)	6.2 (26)	0.8 (90)	0.6 (93)
2150	8.3 (1)	5.3 (37)	0.7 (92)	0.4 (95)
2200	8.2 (2)	4.4 (47)	0.8 (90)	0.3 (97)
		Abyssal cell strength (Sv)		
2000	21.0	21.0	21.0	21.0
2050	21.1 (0)	20.6 (2)	18.1 (14)	15.5 (26)
2100	20.6 (2)	18.8 (11)	12.3 (42)	11.2 (47)
2150	20.0 (5)	16.8 (20)	9.6 (55)	8.0 (62)
2200	19.7 (7)	15.0 (29)	7.3 (65)	5.8(73)

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FW 4.5 and FW 8.5. Although FW 2.6 shows only a gradual slowdown in AABW production, AABW formation rates still decline by more than 40% by 2200. Evidence of continued AABW circulation in 2200 in all three ocean basins in FW 2.6 is a fresh lens of water at *c.* 1000 m depth, with some freshening still appearing in the abyssal layers as meltwater added at the surface is mixed down. In FW 4.5 and FW 8.5 a collapse of AABW is seen in each ocean basin as convection stops, meltwater-induced low salinity water remains at the surface and abyssal waters become more saline. This is particularly significant in the Atlantic.

The three ocean basins are connected by the Antarctic Circumpolar Current, the largest ocean current, which flows eastward through Drake Passage at 58˚S–56˚S / 67˚W. Projections to 2100 by Naughten *et al*. (2018) show a weakening this century of the mean transport by the Antarctic Circumpolar Current through Drake Passage by 13%–16% for RCP4.5 and by 13%–17% for RCP8.5, relative to 1996–2005. Given that Southern Hemisphere westerly winds strengthen in all RCP scenarios, these reductions in transport are likely to stem from ocean freshening around the Antarctic continent, which increases stratification, thereby reducing the meridional density gradient across the Southern Ocean and weakening zonal transport and hence the Antarctic Circumpolar Current.

Changes in Southern Ocean circulation and teleconnections with the three major ocean basins affect global climate, sea level, and ocean biogeochemical cycles.

Climate

Freshening-induced stratification of the water column impedes a relatively warm water mass, Circumpolar Deep Water (which flows in the Antarctic Circumpolar Current and accesses the Antarctic continental shelf) from reaching surface waters, thereby reducing sea surface temperatures (SSTs) and increasing sea ice extent. Simulations show a sea ice anomaly of *c.* 31% in 2055 relative to the pre-industrial mean. Reduced SSTs cool the overlying atmosphere and surface air temperature (SAT) is reduced, thereby reducing the rate of atmospheric warming. The maximum SAT anomaly occurs in 2055, with 0.38 ± 0.02˚C cooling. The IPCC global mean atmospheric warming target of 1.5˚C relative to the pre-industrial period is reached in 2037 without the addition of meltwater, and in 2050 with meltwater added, while 2˚C of warming is reached in 2053 without meltwater and in 2065 with meltwater (Bronselaer *et al*. 2018). The exceeding of the climate warming targets is therefore delayed by more than a decade, as *c.* 0.5˚C–3.5˚C of atmospheric warming is offset (Golledge *et al.* 2019). However, after 2060 ocean warming results in a decrease in sea ice production and a return to the 1950–1970 mean value by 2100.

Simulations also show a meltwater-induced northward shift of the Intertropical Convergence Zone (ITCZ), resulting in the shift of rain northward, with the strongest precipitation change near the Equator. Precipitation changes affect El Niño–Southern Oscillation (ENSO), resulting in Australia becoming drier and Central America less dry. This has consequences for primary productivity and agriculture (Bronselaer *et al.* 2018).

Meanwhile, around the Antarctic coast at *c.* 400 m below sea surface, the depth where water masses are in contact with ice shelf cavities, ocean warming increases, especially in the Ross and Weddell Seas, reaching a maximum in 2100. Enhanced basal melting is incurred and as more meltwater leads to more subsurface warming, positive feedback is produced (Bronselaer *et al.* 2018).

Sea level

Simulations show a collapse of major ice shelves by 2300 in all RCP scenarios above 2.6, causing a long-term commitment (multi-centennial to multi-millennial) to grounded ice discharge from the Antarctic ice sheet owing to the loss of buttressing. The discharge of grounded ice into the ocean resulting from ice shelf mass loss is almost instantaneous, therefore the impact on global sea level is fast. Sea level rises by 0.6–3 m (depending on parameterisations of ice shelf basal melting) by 2300 (Golledge *et al.* 2015). The greatest ice sheet thickness change this century occurs in the Amundsen Sea sector, resulting from the recession of the Thwaites and Pine Island Glaciers (Golledge *et al.* 2019). The entire Antarctic Ice Sheet contains a *c.* 56 m sea level equivalent.

Freshwater anomaly modelling shows a thermostatic sea level rise of 1.5 mm yr^{-1} and halosteric sea level rise (due to haline expansion) of 0-0.3 mm yr^{-1} in 2200 relative to 2000. Haline expansion is greatest in FW2.6 because of the persistence of AABW in this scenario. The highest rates of thermal expansion occur in the Atlantic Ocean and near Antarctica (Lago and England 2019).

Ocean biogeochemistry

Data for Southern Ocean temperature, salinity, pH and concentrations of nitrates, dissolved inorganic carbon (DIC) and oxygen were collected year-round from 2014 to 2019 using biogeochemical sensors on autonomous floats from the Southern Ocean Carbon and Climate Observations and Modelling (SOCCOM). The data were compared to ship-based data from before 2005 to assess changes. South of 65˚S salinity increases by up to 0.2 psu (practical salinity unit) and mean subsurface warming increases by up to 3˚C. Between 65˚S and 40˚S freshening and warming occur, with the greatest warming in coastal regions in the Pacific sector of West Antarctica, particularly at *c.* 400 m depth, the depth of the largest ice shelf basal melt rates. Around the coast south of 65˚S subsurface oxygen and pH decrease by 60 μmol kg^{-1} and over 0.13, respectively, and nitrate and DIC concentrations increase (Bronselaer *et al.* 2020).

An Earth system model (ESM2M) was used to simulate the impact of meltwater and wind on ocean oxygen and nitrate concentrations in the upper 1000 m south of 65˚S and between 60˚S and 0˚S by 2100, relative to the 2014–2019 mean. Forcing by meltwater and poleward-intensified westerly winds were applied using magnitudes comparable to inferred observed changes. Model outputs showed an increase in oxygen concentrations north of 60˚S, which is driven dominantly by meltwater. Concurrently, meltwater significantly increases nitrate concentrations south of 60˚S, whereas they are significantly decreased north of 60˚S as a result of both meltwater and wind (Bronselaer *et al.* 2020).

Using the Community Earth System Model forced with RCP8.5, Moore *et al.* (2018) found that this trend of increased subsurface nutrient concentrations around Antarctica and in the global deep ocean, and a decline elsewhere north of 60˚S, from the surface to the depth of Antarctic Intermediate Water (at *c.* 1500 m) intensifies to 2300 and probably well beyond. It dominates ocean biogeochemistry, as ocean freshening and warming continue to drive stratification. Phosphate and particulate organic carbon (POC) concentrations significantly increase in the Southern Ocean and decline in the tropics by 2300 as a

Table 2 Annual mean values for physical and biogeochemical variables for the high latitude Southern Ocean (south of 60°S) and tropical ocean (30°S–30°N). Values in parentheses show percentage change from the 1850s for some variables (created from data in Moore *et al.* 2018).

	High Latitude				Tropical			
	1850s	1990s	2090s	2290s	1850s	1990s	2090s	2290s
Sea Surface Temperature (°C)	-1.36	-1.22	-0.31	4.6	6.0	26.6	29.2	32.2
SH Sea Ice Area (x10^{16} m^2)	16.0	14.1(-12)	8.4(-47)	0.7(-96)	34.9	34.8	34.8	34.7
Salinity (ppt)	34.0	34.0	33.6	33.1	2.96	3.09	3.52	3.51
Stratificatiom 0–200m (kg/m^3)	0.36	0.43	0.75	1.34	0.523	0.481(-8.0)	0.298(-43)	0.141(-73)
Phosphate 0–100m (µm)	1.84	1.82(-1.1)	1.80(-2.2)	1.68(-8.9)	2.65	2.67	2.64	2.22 (-16)
Phosphate 200–1000m (µm)	2.07	2.07	2.11(1.9)	2.26 (9.2)	0.735	0.735	0.798	0.933
Dissolved Iron 0–100m (nM)	0.194	0.194	0.184(5.2)	0.173(11)	0.595	0.598	0.628	0.698
Dissolved Iron 200–1000 (nM)	0.269	0.283(5.2)	0.303(13)	0.360(34)	81.9	74.9	74.5	75.4
Oxygen 200–1000m (µm)	247	244	226	181	35.0	34.8	32.5(-7.1)	26.9(-23)
NPP (Pg C/yr)	1.06	1.15(8.5)	1.30(23)	1.67(58)	17.0	16.7	14.5	10.5
% NPP by Diatoms	47.1	47.1	44.0	42.7	4.36	4.28(-1.8)	3.72(-15)	2.67(-39)
POC Export (Pg C/yr)	0.275	0.302(9.8)	0.322(17)	0.372(35)				

result of nutrient trapping (Table 2). The transfer of nutrients to the deep ocean is driven by three distinct processes. First, the nutrient flux from the deep ocean to the upper ocean in the northward-subducting Antarctic Intermediate and Subantarctic Mode waters, which is the primary pathway for nutrients to return to the upper ocean, is lowered owing to Southern Ocean nutrient trapping. Second, a global-scale increase in stratification decreases vertical mixing between the upper and deep ocean. Third, a decline in North Atlantic Deep Water (NADW) formation decreases the main source of lower-nutrient waters to the deep ocean, driving nutrient declines that are greater in the Atlantic basin and high northern latitudes than in other regions.

Glacial meltwater contains significant amounts of biologically available iron, dFe, which is taken up by phytoplankton. Subsurface Fe increases by 34% south of 60˚S by 2300, with the highest concentrations near Antarctica, resulting from meltwater and nutrient trapping. The Fe upwelling flux increased by 276% by 2300 relative to pre-industrial levels (Moore *et al.* 2018). An ESM output indicates that *c.* 30% of POC flux through the Southern Ocean at 100 m depth is driven by glacial iron, which results in an uptake of 0.14 Pg carbon yr^{-1} (1 petagram = 1015 grams), thus reducing carbon outgassing by 30% (Laufkötter *et al.* 2018). Through uptake by phytoplankton, glacial iron could therefore remove carbon from the atmosphere on a multi-centennial timescale. Net primary production (NPP) increases by 58% south of 60˚S. However, a 24% decline in NPP north of 30˚S more than off set this increase, driving global-scale NPP declines of 15% and biological export of 30% by 2300 (Table 3). The smallest phytoplankton benefit most from ocean warming and surface water nutrient depletion, outcompeting larger phytoplankton such as diatoms, with zooplankton productivity closely tracking phytoplankton. The largest decline in phytoplankton (56%)and zooplankton (54%) occur in the North Atlantic, with a global decline of 16% and 19% respectively by 2300. A shift to smaller plankton species reduces the efficiency of the biological pump (Table 4). These declines drive a decline in higher trophic levels, which lowers fisheries yields by 22% globally and 59% in the North Atlantic (Table 5).

Conclusions

Earth Systems Models show declines in marine NPP during the 21st century in scenarios with continued high levels of greenhouse gas emissions, but with increasing Southern Ocean NPP as a result of nutrient trapping. The cumulative effects of climate change to 2300, strongly influenced by the Southern Ocean, show a global-scale suppression of marine biological productivity for a millennium, owing to the time necessary for ocean circulation to return

Table 3 Global-scale annual mean values for physical and biogeochemical variables. Values in parentheses show percentage change from the 1850s for some variables (created from data in Moore *et al.* 2018).

Flux Concentration	1850s	1990s	2090s	2290s
Sea Surface Temperature (°C)	18.0	18.6	21.2	25.0
Sea Surface Salinity (ppt)	34.3	34.3	33.5	33.7
NH Sea Ice Area (x10^{16} m^2)	11.7	10.3(-12)	5.08(-57)	0.100(-99)
SH Sea Ice Area (x10^{16} m^2)	16.0	14.1(-12)	8.43(-47)	0.702(-96)
Stratification 0-200m (kg/m^3)	2.00	2.11(5.5)	2.48(24)	2.71(36)
Stratification 500-1500m (kg/m^3)	0.719	0.755(5.0)	0.890(24)	1.54(114)
Stratification 1000-2000m (kg/m^3)	0.322	0.346(4.2)	0.389(17)	0.668(101)
Phosphate 0-100m (µm)	0.627	0.579(-7.7)	0.419(-33)	0.253(-60)
Net Primary Production (Pg C/yr)	55.7	55.8	53.7(-3.6)	47.2(-15)
% NPP by Diatoms	37.9	37.8	32.1 (-15)	24.3 (36)
NNP north of 60°N (Pg C/yr)	1.87	1.92(2.7)	1.91(2.1)	1.22(-35)
NPP 30°N - 60°N (Pg C/yr)	6.65	6.71	6.30(-5.3)	5.0(-25)
NPP 30°S - 30°(Pg C/yr)	34.9	34.7	32.5(-6.9)	26.9(-23)
NPP 30°S - 60°S (Pg C/yr)	11.2	11.3	11.7(4.5)	12.4(11)
NPP south of 60°S (Pg C/yr)	1.06	1.15(8.5)	1.31(23)	1.67(58)

Table 4 Annual mean phytoplankton net primary productivity (NPP) and zooplankton productivity (Z) for the 1990s, 2090s and 2290s in the tropics, Southern Ocean (SO), North Atlantic (N Atl), North Pacific (N Pac), and global. Units are in Pg C/year. Numbers in brackets represent % change relative to the 1990s (created from data in Moore *et al.* 2018).

Region	NPP 1990s	NPP 2090s	NPP 2290s	Z 1990s	Z 2090s	Z 2290s
Tropics	35.02	32.72 (-6.6)	27.12 (-23)	8.01	7.29 (-9.0)	5.71 (-29)
SO	1.16	1.31 (13)	1.68 (45)	0.23	0.27 (21)	0.37 (65)
N Atl	4.14	3.49 (-16)	1.83 (-56)	0.86	0.79 (-8.8)	0.40 (-54)
N Pac	4.05	4.32 (6.6)	4.06 (0.1)	0.87	0.96 (11)	0.95 (8.9)
Global	56.41	54.20 (-3.9)	47.64 (-16)	12.78	12.20 (-4.6)	10.41 (-19)

nutrients to the upper ocean. Some polar-adapted, ice-dependent organisms, including the Antarctic krill essential to the Southern Ocean food web, could become extinct. The depletion of nutrients in the global ocean north of 60˚S and in the upper ocean will not be reversed until the climate cools. The impacts of climate change induced suppression of AABW formation on marine biogeochemistry and productivity is on the same time scale as a collapse of the major ice shelves with subsequent discharge of grounded ice from the Antarctic ice sheet and ensuing sea level rise. The consequences are equally cumulative and catastrophic.

References

Bronselaer, B., Russell, J. L., Winton, M., Williams, N. L., Key, R. M., Dunne, J. P., Feely, R. A., Johnson, K. S., and Sarmiento, J. L. 2020 'Importance of wind and meltwater for observed chemical and physical changes in the Southern Ocean'. *Nature Geosci* **13**, 35–42; https://doi.org/10.1038/s41561-019-0502-8 (accessed 20-06-2020)

Bronselaer, B., Winton, M., Griffies, S. M., Hurlin, W .J., Rodgers, K. B., Sergienko, O. V., Stouffer, R., R. J., and Russell, J. L. 2018 'Change in future climate due to Antarctic meltwater'. *Nature* **564**(7734), 53–8; https://doi.org/10.1038/s41586-018-0712-z (accessed 24-12-2019)

Colling, A. 2001 *S330 Ocean Circulation*. Milton Keynes: The Open University, Chapter 6: Global fluxes and the Deep Circulation

Golledge, N. R., Keller, E. D., Gomez, N., Naughten, K. A., Bernales, J., Trusel, L. D., and Edwards, T. L. 2019 'Global environmental consequences of twenty-first-century ice-sheet melt'. *Nature* **566**(7742), 65–72; https://doi.org/10.1038/s41586-019-0889-9 (accessed 15-03-2019)

Golledge, N. R., Kowalewski, Naish, T. R., Levy, R. H., Gogwill, C. J., and Gasson, E. G. W. 2015 'The multi-millennial Antarctic commitment to future sea-level rise'. *Nature* **526**, 421–5; https://doi-org.libezproxy.open.ac.uk/10.1038/nature15706 (accessed 20-05-2020)

Lago, V., and England, M. H. 2019 'Projected slowdown of Antarctic Bottom Water formation in response to amplified meltwater contribution'. *J Climate* **32**, 6319–35; http://dx.doi.org/10.1029/2018JCO14907 (accessed 09-11-2019)

Laufkötter, C., Stern, A. A., John, J. G., Stock, C. A., and Dunne, J. P. 2018 'Glacial iron sources stimulate the Southern Ocean carbon cycle'. *Geophys Res Let* **45**, 13,377–85; https://doi-org.libezproxy.open.ac.uk/ 10.1029/2018GL079797 (accessed 19-06-2020)

Moore, J. K., Fu, W., Primeau, F., Britten, G. L., Lindsay, K., Long, M., Doney, S. C., Mahowald, N., Hoffman, F., and Randerson, J. T. 2018 'Sustained climate warming drives declining marine productivity'. *Sci Climate Change* **359**, 1139–43; http://science.sciencemag.org/content/359/6380/1139 (accessed 22-07-2020)

Naughten, K. A., Meissner, K. J., Galton-Fenzi, B. K., England, M. H., Timmerman, R., and Hartmut, H. H. 2018 'Future projections of Antarctic ice shelf melting based on CMIP5 scenario'. *J Climate* **31**, 5243–61; https://doi.org/10.1175/JCLI-D-17-0854.1 (accessed 14-12-2019)

Purkey, S. G., Johnson, G. C., Talley, L. D., Slyan, B. M., Wijffels, S. E., Smethie, W., Mecking, S., and Katsumata, K., 2019 'Unabated Bottom Water warming and freshening in the south Pacific Ocean'. *J Geophys Res* **124**, 1778–94; https://doi.org/10.1029/2018JC014775; (accessed 31-03-2020)

Purkey, S. G., Smethie Jr, W. M., Gebbie, G., Gordon, A. L., Sonnerup, R. E., Warner, M. J., and Bullister, J. L. 2018 'A synoptic view of the ventilation and circulation of Antarctic Bottom Water from chlorofluorocarbons and natural tracers'. *Ann Rev Marine Sci* **10**, 503–27; https://doi.org/10.1146/annurev-marine-121916-063414 (accessed 17-02-2020)

Table 5 Annual mean fisheries production at trophic levels 3 (T3) and 4 (T4) for the 1990s, 2090s, and 2290s in the tropics, Southern Ocean (SO), North Atlantic (N Atl), North Pacific (N Pac), and global. Units are in Pg C/year. Numbers in brackets represent % change relative to the 1990s (created from data in Moore *et al.* 2018).

Region	T3 1990s	T3 2090s	T3 2290s	T4 1990s	T4 2090s	T4 2290s
Tropics	0.143	0.130 (-9.1)	0.101 (-29)	0.0150	0.0136 (-9.4)	0.0106 (-29)
SO	0.00540	0.00651 (21)	0.00891 (65)	0.000757	0.000911 (21)	0.00125 (65)
N Atl	0.0168	0.0145 (-13)	0.00705 (-58)	0.00215	0.00182 (-15)	0.000884 (-59)
N Pac	0.0180	0.0188 (4.9)	0.0179 (-0.3)	0.00249	0.00251 (1.0)	0.00228 (-8.3)
Global	0.246	0.232 (-5.7)	0.196 (-20)	0.0290	0.0270 (-6.8)	0.0226 (-22)

Polygonal columnar cooling joints in intermediate and felsitic lithologies, with examples from the English Lake District

Duncan Woodcock

Introduction

The natural patterns formed by polygonal columnar jointing has long been a source of fascination to observers and a subject of scientific study. Many examples were formed as a consequence of the cooling, contraction and fracturing of igneous bodies, such as lava flows and sills, that were emplaced as liquids. In addition, such cooling-contraction columnar jointing can be developed within ignimbrite sheets that were emplaced as pyroclastic density currents, in many instances sufficiently hot for the solid pyroclasts to become welded.

Polygonal jointing can also form by desiccation of fine-grained wet sediments subjected to prolonged dry conditions, although the resulting 'mud crack' networks tend not to develop long columns. Polygonal columns can be produced artificially by leaving a slurry of corn starch in water to progressively dry out. The resulting columns show similarities to those produced by the cooling-contraction mechanism. This is perhaps not astonishing, since both cooling and desiccation are controlled by diffusional processes, either of heat or of water (Muller 1998). Mullineaux *et al.* (2020) report the development of columnar jointing within a bentonite clay deposit in Derbyshire that immediately underlies a dolerite sill. Their petrological studies of the columnar-jointed material indicated dehydration and subsequent shrinkage of the bentonite by prograde contact metamorphism.

Most of the columnar jointing described in the literature appears to occur in basaltic rocks. The spectacular British examples of the Giant's Causeway and on the island of Staffa are beautifully illustrated by Bob Mehew in a recent article in the *Proceedings of the OUGS* (Mehew 2021). At both these locations, hexagonal columns predominate, although this is not necessarily the case at all locations where columnar jointing develops. In a short, rather polemical paper, Beard (1959) counters the implication that "in practically all outcrops, hexagonal prisms predominate" by reporting studies at several sites in the USA and France where pentagonal columns generally predominate. Beard's data set is included in Table 1; it often forms the core of many other published sets of data such as in Budkewitch and Robin (1994).

In the remainder of this article, I review data published for columnar jointing developed within felsic and intermediate lithologies and report my observations from three locations in the Lake District.

Columnar jointing in felsic and intermediate lithologies: published examples

In contrast to the large number of studies of columnar jointing in basalts there appear to be few published studies of columnar jointing within felsic and intermediate lithologies, despite their widespread occurrence in some localities. One such study, by Balin and Petrinec (2014), reports details of cooling-contraction columnar jointing developed within a shallow dacite sill in Croatia. They determined the number of edges of a total of 785 columns and found that pentagonal and four-sided columns predominated. A similar result was obtained by Wright *et al.* (2011) from a study of columnar jointing developed within the rhyodacitic Paycuqui ignimbrite in Argentina.

Beard (1959) included observations from the 264-metre-high Devil's Tower in Wyoming, which displays what is probably the largest scale of columnar jointing in the world. He found that predominantly pentagonal columns with an average diameter of 2–3 m were developed in this porphyritic phonolite intrusion.

Columnar jointing in felsic and intermediate lithologies: examples from the Lake District

Intermediate and felsic rocks are common within the upper Borrowdale Volcanic Group of the Lake District. Many of these are ignimbrites: the deposits from hot, pumiceous pyroclastic density currents that were sufficiently hot to become welded over much of their depth. In this section I describe three locations where columnar jointing is well developed.

Table 1 Distribution of the number of edges of polygonal columns: published data

Location	Lithology	Number of edges (N) 3	4	5	6	7	8	Total count	Mean N
Giant's Causeway, N. Ireland[c]	basalt	0	6	49	102	40	4	201	5.9
Devil's Postpile, California[b]	basalt	2	38	150	178	32	0	400	5.5
Columbia River, Idaho[b]	basalt	0	5	30	28	7	0	70	5.5
Dunsmuir, California[b]	basalt	1	29	92	67	9	2	200	5.3
Mount Rodeix, France[b]	basalt	0	30	100	65	5	0	200	5.2
Craters of the Moon, Idaho[b]	basalt	0	14	28	8	0	0	50	4.8
Burnt Island, Scotland[a]	basalt	6	33	50	24	3	0	116	4.9
Devil's Tower, Wyoming[b]	phonolite	0	17	42	35	6	0	100	5.3
Rupnica, Croatia[d]	dacite	25	325	352	81	2	0	785	4.6
Paycuqui, Argentina[e]	rhyodacite	24	78	72	26	0	0	200	4.5

[a] Sosman 1916, [b] Beard 1959, [c] O'Reilly 1879, [d] Balin and Petrinec 2014, [e] Wright *et al.* 2011

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Figure 1 General view of columnar jointing developed in the Yewdale Ignimbrite at Torver Beck, Coniston (SD 274 963) (beck is 1–2 m wide in this photo).

Torver Beck, Coniston

Columnar jointing occurs on both sides of the beck at SD 274 963 (Fig. 1). The columnar-jointed area is most extensive on the west bank of the beck (Fig. 2), but it is somewhat inaccessible, and it is difficult to examine a large number of columns. There are fewer columns on the east bank, but here columns are well developed with their long axes plunging at 43° to 292° magnetic. Some of these columns show banded striae or 'chisel marks' (Fig. 3). Ryan and Sammis (1978, 1981) explained these striae as the product of intermittent crack advance in response to the cyclical release of tensile stress during cooling-contraction. Thus, as the rock cools it contracts and accumulates tensile strain. When the stress at the tip of the previous crack exceeds the tensile strength of the rock, a new crack increment propagates up-temperature as far as the glass transition temperature isotherm.

Figure 2 Columnar jointing on the west bank of Torver Beck (field of view c. *1.5 m × 2 m).*

Figure 3 Columnar joints, c. *200 mm wide, on the east bank of Torver Beck showing banded striae ('chisel marks') approximately orthogonal to the long axes of the columns.*

The location described above lies within the lower part of the Yewdale Ignimbrite (Millward 1980), a welded ignimbrite with a total thickness of 85 m, within which columnar jointing is variably developed. Millward (1980) noted that four-sided columns predominated, although five-sided columns were 'quite abundant'.

Foul Scrow, Coniston

A small area of columnar jointing is exposed on the west face of a low crag, immediately east of a drystone wall at SD 2922 9777 (Fig. 4). There is an additional exposure on the top of the crag at SD 2927 9775. Column faces are typically 50–150 mm wide and columns plunge at 43° to 294° magnetic. Some columns show 'chisel marks' (Fig. 5, *opposite*), similar to those at Torver Beck. The columns have developed in a medium-grey, fine-grained, sparsely plagioclase-phyric rock that shows a welding fabric on some weathered surfaces. These rocks are part of the Lincomb Tarns Formation, and are probably a dacitic welded lapilli tuff (BGS, 1996).

Figure 4 General view of columnar jointing at Foul Scrow, Coniston (SD 293 978) (hammer is 280 mm long).

Figure 5 'Chisel marks' on a column face at Foul Scrow (hammer handle width is 40 mm).

A total of 37 columns were sufficiently well exposed to enable numbers of faces to be determined. In addition, 19 columns were observed in the adjacent drystone wall, where they had been used as capstones and as throughstones. Table 2 *(overleaf)* summarises the data collected and shows an overall predominance of pentagonal columns.

Yewry Sike, Broughton Moor

Columnar jointing is extensively exposed along the north bank of Yewry Sike, a tributary of the R. Lickle, at SD 245 946 (Fig. 6). This area has been quarried for columns in past times for local use as throughstones in drystone walls (Fig. 7, *overleaf*) and as rails in water yeats (Fig. 8, *overleaf*). This location lies within the Lag Bank Formation, described as a "poorly sorted, massive dacitic lapilli tuff" (Fig. 9, *overleaf*) that is moderately to densely welded (Millward *et al.* 2000).

Four locations, spread over a distance of *c.* 60 m, showed sufficiently good exposure to be able to count the numbers of sides of the columns. Figure 10 *(overleaf)* shows one of the more photogenic surfaces available. Table 3 *(overleaf)* summarises the data for these locations, which overall show a predominance of pentagonal columns.

Summary and conclusions

Figure 11 *(page 127)* attempts to summarise the 12 sets of data reviewed in this article. This composite histogram shows the distributions of the proportion of polygons with a given number (N) of edges. The seven distributions for basaltic columns are variously shaded in orange and presented in the same order as in Table 1; thus, the first orange bar, for each N, shows the proportions for the Giant's Causeway, which are identical to Figure 8 in Mehew (2021). The five distributions for columns of intermediate and felsic lithologies are presented in more intense colours for comparison. These include the three sets of published data in Table 1 together with my data from Foul Scrow and Yewry Sike in the Lake District.

Figure 6 Columnar jointing exposed along the north bank of Yewry Sike, Broughton Moor (SD 245 946). The columns are typically 100–200 mm in diameter and plunge at 70–80° to 250° magnetic.

Figure 7 A column used as a throughstone in a dilapidated drystone wall at Yewry Sike (hammer is 280 mm long).

Figure 8 Columns used as rails in a water yeat within a drystone wall at SD 2345 9320, near Stephenson Ground, a couple of miles south of the quarry at Yewry Sike.

Table 2 Distribution of the number of edges of polygonal columns at Foul Scrow, Coniston

Location	Number of edges (N) 3	4	5	6	7	8	Total count
Face of crag SD 2922 9777	0	13	9	3	0	0	25
Top of crag SD 2927 9775	0	1	9	2	0	0	12
Drystone wall	0	2	10	6	1	0	19
Total for Foul Scrow	0	16	28	11	1	0	56

Table 3 Distribution of the number of edges of polygonal columns at Yewry Sike, Broughton Moor

Location	Number of edges (N) 3	4	5	6	7	8	Total count
Location 1 SD 2458 9464	4	6	15	8	0	0	33
Location 2 SD 2457 9464	1	4	8	6	1	0	20
Location 3 SD 2457 9464	2	8	28	26	2	0	66
Location 4 SD 2455 9462	5	29	85	38	9	1	167
Total for Yewry Sike	12	47	136	78	12	1	286

Figure 9 Fresh surface of the welded tuff in a broken column at Yewry Sike.

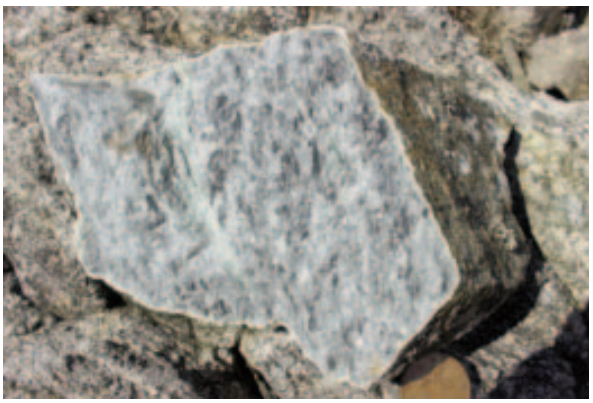


Figure 10 Polygonal jointing pattern at Yewry Sike. This example is unusually regular, with a predominance of hexagonal columns, which makes it worth photographing.

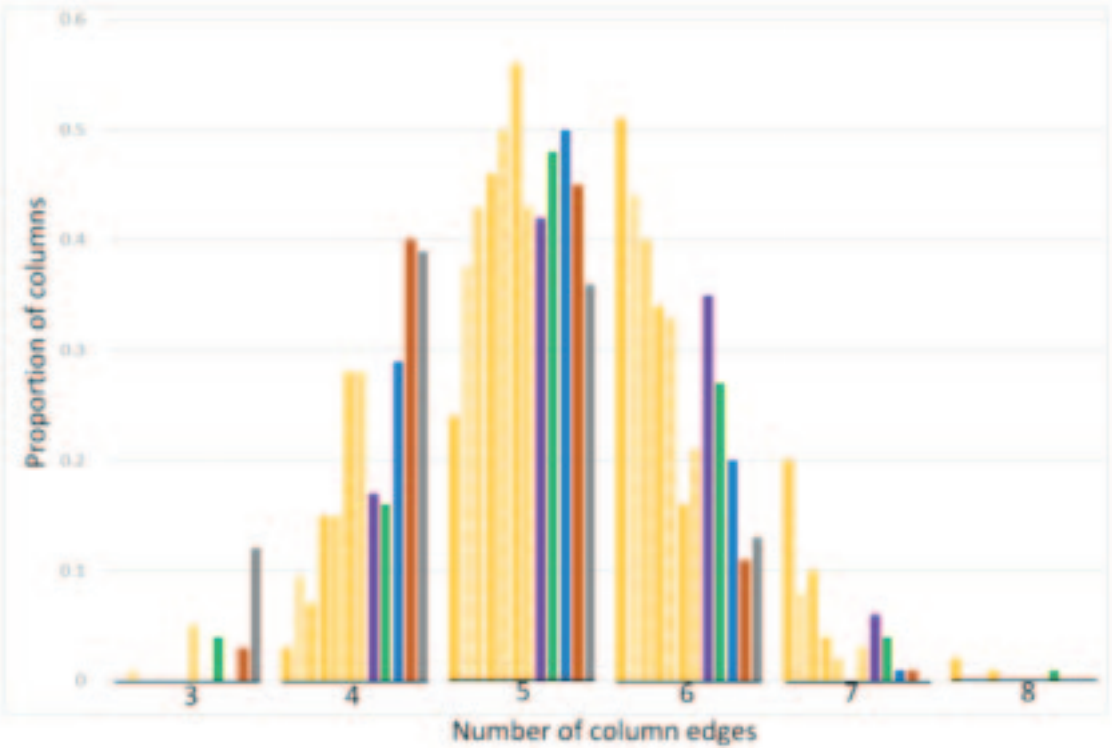


Figure 11 A composite histogram showing the distributions of the proportion of polygons with a given number (N) of edges. The seven distributions for basaltic columns are variously shaded in orange and presented in the same order as in Table 1. The five distributions for columns of intermediate and felsic lithologies are as follows: Devil's Tower (purple), Yewry Sike (green), Foul Scrow (blue), Rupnika (brown) and Paycuqui (grey).

Figure 12 The Organ Pipes, near Melbourne, Victoria. Columns up to 20 m long developed in a Pleistocene basaltic lava flow.

Two conclusions can be drawn from a study of Figure 11. First, for the basaltic columns, pentagonal columns predominate in five of the locations. Hexagonal columns predominate at the Giant's Causeway and Devil's Postpile — both locations that are renowned for the regularity of the patterns produced. Philips *et al.* (2013) indicate that hexagonal columns also predominate at Staffa, although data for this location is not included in Figure 11. Second, for intermediate and felsic lithologies, pentagonal columns predominate, although at one locality four-sided columns were most common.

Overall, there appears to be a tendency for a reduction in the number of column edges in felsites and intermediate lithologies compared to basalts. If this is indeed a real effect, the cause is, at present, unknown.

Acknowledgements

I am indebted to Dr Clive Boulter for bringing the Yewry Sike location to my attention. I am also grateful to my past employers for providing opportunities to visit columnar jointing locations in New England, USA and Victoria, Australia (Fig. 12).

Figure 13 This almost regular pentagonal column was collected from Torver Beck more than 40 years ago and now resides in our garden. It epitomises my fascination with columnar jointing, which began in the Kenya Rift Valley in the late 1950s.

References

Balin, D., and Petrinec, Z. 2014 'Development of columnar jointing in albite rhyolite in a rapidly cooling volcanic environment (Rupnica, Papuk Geopark, Croatia)'. *Terra Nova* **26**, 102–10

Beard, C. N. 1959 'Quantitative study of columnar jointing'. *Bull Geol Soc Amer* **70**, 379–82

British Geological Survey 1996 *Ambleside, England and Wales Sheet 38, Solid Geology*, 1:50 000. Keyworth, Nottingham

Budkewitsch, P., and Robin, P-Y. 1994 'Modelling the evolution of columnar joints'. *J Volcanol Geothermal Res* **59**, 219–39

Mehew, R. 2021 'The formation of columnar basalt'. *Proc OUGS* **7**, 15–19

Millward, D. 1980 'Three ignimbrites from the Borrowdale Volcanic Group'. *Proc Yorks Geol Soc* **42**, 595–616

Millward, D., Johnson, E. W., Beddoe-Stephens, B., Young, B., Kneller, B. C., Lee, M. K., and Fortey, N. J. 2000 *Geology of the Ambleside district, Memoir for the 1:50 000 Geology Sheet 38 (England and Wales)*. Keyworth, Nottingham

Muller, G. 1998 'Experimental simulation of basalt columns'. *J Volcanol Geothermal Res* **86**, 93–6

Mullineux, S., Sparks, R. J., Murphy, M. D., MacNiocaill, C., Barfod, D., Najorka, J., and Schumacher, J. C. 2020 'Columnar-jointed bentonite below a doleritic sill, Tideswell Dale, Derbyshire, UK: formation during prograde contact metamorphism'. *Geol Mag* **157**, 1181–98

O'Reilly, J. P. 1879 'Explanatory notes and discussion on the nature of the prismatic forms of a group of columnar basalts Giant's Causeway'. *Trans Roy Irish Acad* **26**: 641–728

Phillips, J. C., Humphreys, M. C. S., Daniels, K. A., Brown, R. J., and Witham, F. 2013 'The formation of columnar joints produced by cooling in basalt at Staffa, Scotland'. *Bull Volcanol* **75**, 715

Ryan, M. P., and Sammis, C. G. 1978 'Cyclic fracture mechanism in cooling basalt'. *Bull Geol Soc Amer* **89**, 1295–308

Ryan, M. P., and Sammis, C. G. 1981 'The glass transition in basalt'. *J Geophys Res* **86** (part B), 9519–35

Sosman, R. B. 1916 'Types of prismatic structure in igneous rocks'. *J Geol* **24**, 215–34

Wright, H. M. N., Lesti, C., Cas, R. A. F., Porreca, M., Viramonte, J. G., Folkes, C. B., and Giordano, G. 2011 'Columnar jointing in vapor-phase-altered, non-welded Cerro Galán Ignimbrite, Paycuqui, Argentina'. *Bull Volcanol* **73**, 1567–82

The Cambrian Explosion: a theory

Brian R. J. Glover

Figure 1 Fig 1 Early Cambrian fauna (image licensed from Getty Images [UK]).

Introduction

It has long been suggested that the driver of the explosion in complex life during the Cambrian Period was the dramatic increase in atmospheric oxygen as a result of two 'Oxygen Events' during the Proterozoic Eon (Fig. 1).

This theory postulates that the substantial increase in oxygen levels during this time resulted in an extinction event that killed off most anaerobic life in Earth's oceans and enabled the evolution of complex oxygen-breathing organisms to fill the resultant faunal gap.

Such extinction events have occurred several times during Earth's history, and in each case the empty ecological niches were filled by new life. For example, the end-Permian extinction that killed off all large amphibians paved the way for the rise of reptiles; and the end-Cretaceous extinction that killed off the dinosaurs and marine reptiles paved the way for the rise of mammals.

However, was oxygen the only driver at the time of the 'Cambrian Explosion'? There is a second possibility that could have made not only a major contribution, but also provides an explanation of why complex life failed to develop earlier in Earth's history: the absence or presence of an ozone layer in Earth's atmosphere.

Atmosphere of the early Earth

During the Archean Eon (4 Ga–2.5 Ga) Earth's atmosphere contained only carbon dioxide (CO_2), methane (CH_4), water vapour (H_2O), carbon monoxide (CO), a little nitrogen (N) and hydrogen (H) (Borzenkova and Turchinovich 2009).

Fauna of the early Earth

During the Archean and much of the Proterozoic most lifeforms were of marine purple and green sulphur bacteria and algae, blue-green stromatolites and multicellular metazoans, all of which utilised anaerobic photosynthesis to generate energy, i.e. sunlight used to split molecules of water, sulphur, iron or hydrogen sulphide (Nalin 2013).

Unlike oxygenic photosynthesis, the waste products produced through anaerobic photosynthesis are carbon dioxide and methane instead of oxygen.

Oxygenation events

The Great Oxygenation Event (GOE) occurred during the Palaeoproterozoic Era *c.* 2.4 Ga– 2.0 Ga. The result of this event was to increase free oxygen in Earth's atmosphere from 0.0001% to *c.* 1–2% (Ligrone 2019).

The Neo-Proterozoic (also called the 'Second') Oxygenation Event (NOE) occurred during the Neoproterozoic Era *c.* 0.85 Ga–0.54 Ga. The result of this event was to increase free oxygen in Earth's atmosphere from 1–2% to *c.* 10% (Holland 2006) (Fig. 2).

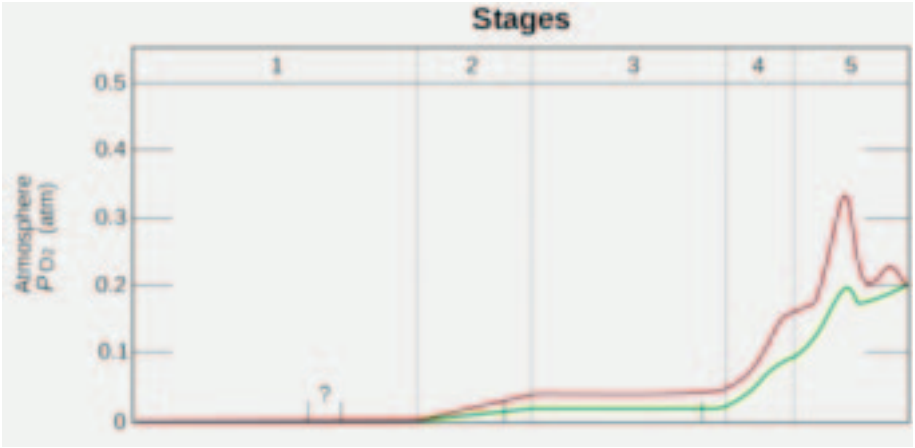
Importance of ozone

Solar UV radiation covers the wavelength range 100–400 nm and is divided into three bands:

UV-A (315–400 nm): the most damaging type of UV at the Earth's surface
UV-B (280–315 nm): cannot penetrate beyond superficial skin layers
UV-C (100–280 nm): potentially the most damaging type of ultra-violet radiation of all (World Health Organisation 2016).

Currently 50% of UV-A, 90% of UV-B-and 100% of UV-C is absorbed by the ozone layer (National Aeronautics and Space Administration 2021) (Fig. 3, *overleaf*). Studies by the US National Aeronautics and Space Administration (NASA) show

Figure 2 Estimated evolution of atmospheric PO2. The upper red and lower green lines represent the range of the estimates. The stages are: stage 1 (3.85 Ga–2.45 Ga); stage 2 (2.45 Ga–1.85 Ga); stage 3 (1.85 Ga–0.85 Ga); stage 4 (0.85 Ga–0.54 Ga); and stage 5 (0.54 Ga–present) (© Heinrich D. Holland, reproduced with permission under GNU: Free Documentation License).



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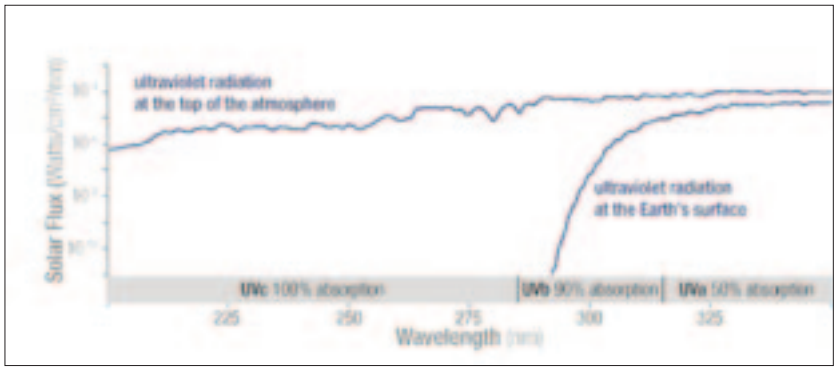


Figure 3 Solar UV levels and absorbency by the ozone layer (permission courtesy of NASA Ozone Watch).

that today the ozone represents only 0.00006% of the atmosphere, while oxygen is *c.* 20%. The results of these studies suggest that before the NOE a 1–2% oxygen saturation would have meant that ozone was only produced at levels of *c.* 0.000005%; that is, 92.5% less than the level today.

Even taking into account the fact that during the time interval of 4.5 Ga to 1 Ga, solar luminosity was 5% to 20% lower than at present, with no ozone layer, levels of solar UV radiation reaching the surface of the Earth before the NOE was likely to have been up to 1,000,000 times greater than it is today (National Aeronautics and Space Administration 2010; Blumthaler, Ambach and Ellinger 1997; World Health Organisation 2002).

Effect of solar UV radiation on biology

It is estimated that during the Proterozoic, marine organisms were most abundant in coastal and ocean environments within the first 5 m to 25 m depth zone (Butterfield 2007; Avila-Alonso, Baetens, Cardenas and De Baets 2017).

Today UV radiation penetrates seawater to a depth of between 20 m and 40 m, depending on the clarity of the water. But with no ozone layer to absorb UV radiation, penetration is likely to have been to much deeper depths (Fleischmann 1989).

The effects of UV radiation on living organisms include the destruction or inactivation of proteins, the destruction of cell membranes, and damage to strands of ribonucleic acid (RNA) and deoxyribonucleic acid (DNA), causing mutations and cell death (Sutherland 2006; Gao *et al.* 2019; Sinha and Hader 2002) (Fig 4).

UV-A and UV-B radiation also inhibits photosynthetic production, and therefore also reduces carbon dioxide intake. Studies have shown that UV-A, in particular, can significantly decrease photosynthesis by more than 70% (White and Jahnke 2002).

Conclusion

With no free oxygen in the Earth's atmosphere up to the end of the Archean Eon the triatomic allotrope of oxygen produced by the reaction of solar ultra-violet radiation on oxygen molecules — ozone — could not have existed (Chapman 1930).

Following the Great Oxygenation Event, the amount of ozone that could have been produced from the very limited quantities of free oxygen available in the atmosphere provided only a marginal reduction in the levels of UV radiation reaching the Earth's surface.

Continual exposure to extremely high levels of solar UV radiation — especially UV-C radiation that today no longer reaches the Earth's surface — is likely to have inhibited critical life functions and to have produced high levels of genetic damage. Both these factors would have had a significant detrimental effect on the health, longevity, reproductive capability and evolution of Precambrian organisms.

Only after the Neo-Proterozoic Oxygenation Event *c.* 0.85 Ga–0.54 Ga could an effective ozone layer have been formed and created an environment that enabled Cambrian organisms to develop and flourish.

A final thought: Can it be just a coincidence that eyes — organs particularly susceptible to serious damage from UV-C radiation — evolved from simple photoreceptors only after the Neo-Proterozoic Oxygenation Event? The evidence suggests perhaps not (Hazlehurst and Hendry 2017).

References

Avila-Alonso, D., Baetens, J., Cardenas, R., and De Baets, B. 2017 'Assessing the effects of ultraviolet radiation on the photosynthetic potential in Archean marine environments'. *Internat J Astrobiol* **16**, 271–9

Blumthaler, M., Ambach, W., and Ellinger, R. 1997 'Increase in solar UV radiation with altitude'. *J Photochem Photobiol* **39**, 130–4

Borzenkova, I. I., and Turchinovich, I. 2009 *Environmental Structure and Function: Climate System (Volume II): History of Atmospheric Composition*. Paris: UNESCO

Butterfield, N. J. 2007 'Macroevolution and macroecology through deep time'. *Paleontol* **50**, 41–55

Chapman, S. 1930 'A theory of upper-atmospheric ozone'. *Mem Roy Meteorol Soc* **3**, 103–25

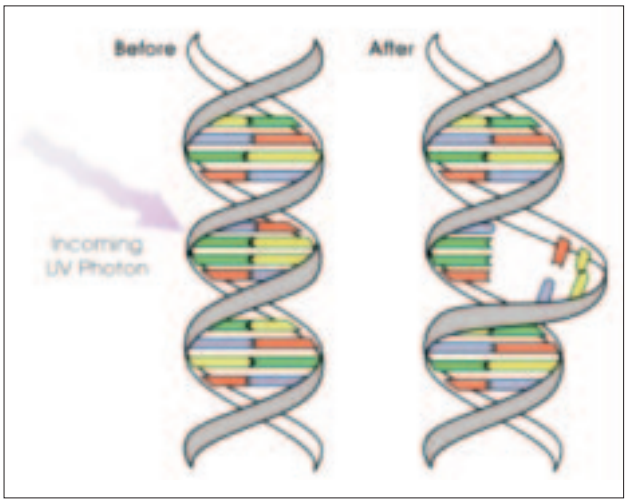
Fleischmann, E. M. 1989 'The measurement and penetration of ultraviolet radiation into tropical marine water'. *Limnology and Oceagraphy* **34**, 1623–9

Gao, K., Beardall, J, Häder, D-P., Hall-Spencer, J. M., Gao, G., and Hutchins, D. A. 2019 'Effects of ocean acidification on marine photosynthetic organisms under the concurrent influences of warming, UV radiation, and deoxygenation'. *Front Mar Sci* 6**,** article 322 [18pp]

Hazlehurst, K., and Hendry, L. 2017 *Eyes on the prize: the evolution of vision*. London: Nat Hist Mus: https://www.nhm.ac.uk/discover/eyes-on-the-prize-evolution-of-vision.html

Holland, D. H. 2006 'The oxygenation of the atmosphere and oceans'. *Philosoph Trans Roy Soc Lond B: Biol Sci* **29;361(1470)**, 903–15

Figure 4 UV radiation damage to DNA (© David Herring: I, the copyright holder of this work, release this work into the public domain. This applies worldwide).



Ligrone R. 2019 'The great oxygenation event', in Roberto Ligrone *Biological Innovations that Built the World*. Cham: Springer, Cham, 129–54

Nalin, R., 2013 'Traces of life from Archean rocks: evidence and challenges'. Linda Loma, California: Geoscience Research Institute, https://grisda.org/traces-of-life-from-archean-rocks-evidence-and-challenges-1

National Aeronautics and Space Administration, Science Mission Directorate 2010 'Ultraviolet waves'. NASA Science: http://science.nasa.gov/ems/10_ultravioletwaves

National Aeronautics and Space Administration 2021 *Ozonewatch*. ozonewatch.gsfc.nasa.gov

Sinha, R. P., and Hader, D. P. 2002 'UV induced damage'. *Photochem Photobiol Sci* **1**, 225–36

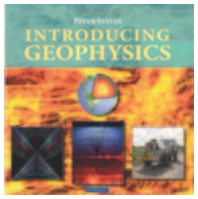
Sutherland, B. M. 2006 *Medical and Environmental Effects of UV Radiation*. New York: Brookhaven National Laboratory

White, A. L., and Jahnke, L. S. 2002 'Contrasting effects of UV-A and UV-B on photosynthesis and photoprotection of β-carotene in two *Dunaliella* spp.' *Plant and Cell Physiol* **43**, 877–84

World Health Organisation 2002 *Global Solar UV Index — a Practical Guide*. Geneva :WHO/SDE/OEH/02.2, 1–18

World Health Organisation 2016 'Q&A detail, radiation-ultraviolet-(uv)': https://www.who.int/news-room/questions-and-answers/item/radiation-ultraviolet-(uv)

Book Review



Styles, P. 2021 *Introducing Geophysics*. Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-080-2; 117pp; paperback £14.99

This short but informative book is a further addition to the series of introductory books on earth sciences produced by Dunedin. It demonstrates the importance of geophysics in an introductory and engaging way. Almost all of our knowledge about the subsurface of the Earth, from a few tens of metres down to the centre of the core, has come from geophysical studies. Fortunately, the Earth is a large and slow-moving body, so we can ignore both quantum physics and relativity; the principles of geophysics can be developed by the use of classical physics together with mathematics. In this book the author has minimised the maths to make the volume as accessible and attractive as possible.

Most of the book concentrates on 'pure' geophysics. Thus, the principles of heat flow, seismology, geomagnetism and gravity are clearly explained, with an emphasis on understanding the deep structure of the Earth. A chapter on the electrical properties of the Earth, provides an introduction to the techniques of self-potential, electrical resistivity and electromagnetic imaging, all of which play a major role in applied geophysics.

The final chapter of the book is entitled 'Geophysics goes to work'. It shows how geophysics can be used in our ongoing quest to find resources in the subsurface, both to "get stuff" we want, like hydrocarbons and to "put stuff" that we do not want, like radioactive waste. In addition, geophysics can be used to detect dangerous ground — such as developing solution cavities — and to "de-risk" major infrastructure projects by providing a detailed view of the subsurface that is to contain the foundations. Many readers will be familiar with the use of geophysics in archaeological investigations from the *Time Team* programmes on TV. Finally, the speciality of forensic geophysics, in particular the detection of clandestine burials, is currently developing into a technique of great assistance to the police services.

Many of these applications of geophysics make use of more than one technique to solve the problem in hand, with the techniques chosen to complement each other and so minimise the uncertainty associated with the use of a single technique.

This book succeeds admirably as an introduction to geophysics and should be of interest to a wide readership. I noticed a few errors during review, but none of these will lead the reader seriously astray. Once the reader has worked through this book, he/she will be in a good position to tackle some of the more advanced books suggested in the 'Further Reading' suggestions.

The book is well illustrated with clear diagrams and pictures, and supported by a detailed and comprehensive glossary of more than 140 entries that are also referenced back to the main text, doubling its use as an index. The book has a strong binding and cover, so it should stand up to plenty of use. At £14.99 it is a bargain.

— Duncan Woodcock, MA (Cantab),BSc (Hons) (Open), PhD, Continuing ES student

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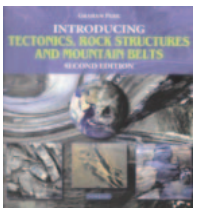
Book Review



Park, G. 2021 Introducing Tectonics, Rock Structures and Mountain Belts (2nd edn). Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-094-9; 135pp; paperback £14.99)

This is a great little book that provides an introduction to earth structures on a wide range of scales, starting with the structure of the Earth and plate tectonic theory. This is then used as a context in which to look at deformation, fractures and faulting, folding, and fabrics such as schistosity and gneissosity. The final few chapters of the book are dedicated to orogenic belts, both modern and ancient, showing how a knowledge of structures can aid our understanding of these exciting regions.

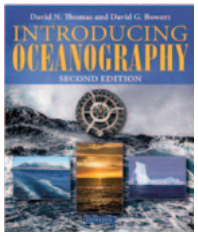
The author, Graham Park, is Emeritus Professor of Tectonic Geology at the University of Keele. He has deliberately steered away from a textbook containing a rigorous mathematical approach to the subject of structures, and has instead kept the geometry to the minimum required for the concepts to be understood.

The book is well illustrated, both with schematics illustrating the concepts, and a wide array of colour photographs showing field examples, all of which are well referenced in the text and aid understanding of the structures described. There is also an excellent glossary, which is handy as a quick reference for structural terms.

This book would be a great read for anybody studying S209 or S309 with the Open University, to help consolidate what they have learned or for anyone wishing to gain an introduction to the subject.

— Louisa Perryman, OU Earth Science Student

Book Review



Thomas, David N., Bowers, and David G. 2021 *Introducing Oceanography* (2nd edn). Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-095-6; 191pp; paperback £9.99)

We are at the start of the United Nations Decade of the Oceans for Sustainable Development (2021–2030) and so it seems fitting to receive a revised second edition of *Introducing Oceanography* in support of such a global campaign at the present time. The original book was part of a series covering various geological and geology-related titles such as *Geomorphology*, *Meteorology*, *Sedimentology*, *Metamorphism*, *Vulcanicity* and *Tectonics*, to name but a few of the 17 titles. The passion for the authors' area of interest is evident throughout. David N. Thomas, a Professor of Arctic Ecosystems Research at the University of Helsinki in Finland, and David G. Bowers, recently retired from the school of Oceanographic Sciences at Bangor University, Wales, both having a wealth of experience in this field.

The Preface to the book sets out the critical importance of the study of Oceanography to ourselves and to the planet in the past, present and future; and it is here that the logic of the book's presentation is set out. Alongside this, the section includes several graphical presentations to illustrate the complexity of the subject matter: a tangled web diagram, which astounds our awareness of these complexities and interconnectivities; the Spilhaus map projection, centred on Antarctica, showing the world's oceans forming a single, uninterrupted body of water and displaying sea surface temperatures ranging from –1.8˚C to 35˚C giving us a picture of how the oceans link and their currents spread heat; and a graph displaying ocean processes from a one-second timescale molecular process through to global ocean circulation patterns over thousands of years. We are left in no doubt about the range of scales and complexities involved.

The chapters proceed logically, giving an overview of a wealth of subject matter, clearly and concisely explaining and expanding on ideas introduced in the opening chapter. There is no getting bogged down with detail or taking too large an academic step into scientific equations and controversial debates , which can be distracting. It seeks to aid our understanding by presenting the artistry of the 'ocean system' in a conversational, but by no means simplistic, style!

The initial chapters describe the oceans and the forces at work within them with yellow text boxes supplying additional information, often of a quantitative nature. The effects of light and life in the oceans is presented before succinctly tackling the chemistry of the oceans. Marine organisms are greatly influenced by the medium in which they live and can modify it. The linkages between the living and non-living reservoirs are neatly explained and illustrated with global examples. Chapters dealing with 'Density and density flows', 'Flows in the ocean', 'Ocean waves', 'Tides and shelf seas' follow on in a similar format.

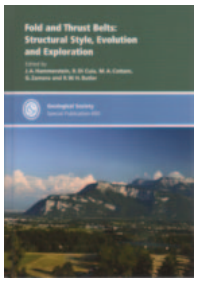
The final two chapters look to the future with a consideration of changes brought about by global climate change, ocean acidification, eutrophication, the presence of plastics and the effect of tidal friction causing gradual slowing of the Earth's spin. At this point too, we are introduced to methods of ocean data capture and the importance of long-term data sets for our understanding of the changes occurring due to short term variability compared with long-term change.

It is quite a readable, inclusive volume, providing a succinct introduction to the intricacies in the workings of our oceans, well supported by text explanation, many clear and appropriate photographs and satellite images, and yellow boxes highlighting focused material, all of which help to cater for a range of readers. A concise but clear 'Glossary' adds detail to some technical terms and a useful 'Further Reading' section enables the reader access to the vast online literature and provides a useful springboard into the subject.

The book is excellent value for money and will appeal to A level students, undergraduates and anyone, in fact, whose interest has been piqued by media articles, news reports or who has an interest or concern for our planet.

— Sue Hughes, BSc Hons (Open), MA (Ed)

Book review



Hammerstein, J. A., Di Cuia, R., Cottam, M. A., Zamora, G. and Butler, R. W. H (eds) *2020. Fold and Thrust Belts: Structural Style, Evolution and Exploration*. London: Geological Society Special Publication 490 (ISBN 978-1-78620-447-9; 444pp; hardback £120)

As for all Geological Society Special Publications, this book is not intended as a textbook, but rather to provide balanced coverage of the latest research in the field of the fold and thrust belts that often characterise the outer parts of collision mountain belts.

Much of our understanding of these regions has been driven by hydrocarbon exploration and it is believed that fold and thrust belts have further potential as hosts for hydrocarbon reservoirs. However, these regions are often inaccessible, and their complex geology, weathering, topography and presence of salt can all mean that the quality of subsurface imaging is poor.

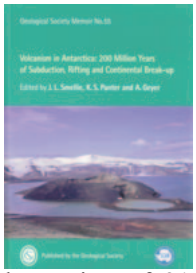
For this reason, it can be useful to model the structures using analogue materials. Papers within this book cover the use of modelling in understanding how strain is distributed within folds and faults, and how the rate of syn-kinematic sedimentation relative to thrust displacement rate influences the style of fold and thrust belts.

The book also includes field studies from Europe, Asia-Pacific and the Middle East, including work on how crustal strength and pre-existing structures affect the development of fold and thrust belts, and highlighting the need to use a multi-disciplined approach, in order to overcome the challenges in interpreting seismic data.

For those who are current students or staff of the Open University, this publication can be accessed online in the Lyell Collection, via the Open University Library.

— Louisa Perryman, OU Earth Science Student

Book review



Smellie, J. L, Panter , K. S., and Geyer, A. (eds) 2021 *Volcanism in Antarctica: 200 Million Years of Subduction, Rifting and Continental Break-up*. London: Geological Society Memoir 55 (ISBN 978-1-78620-536-0; 816pp; hardback £210)

This Geological Society Memoir is an amalgamation of 31 papers, each denoting a chapter, with abstracts, PDFs and references and full text HTML. Starting with an introduction by the editors, the papers that follow are organised into seven sections. The first explains Antarctica's tectonic history and gives an overview of its volcanism over the past 200 million years. The four subsequent sections each present distinct tectonic settings in different regions of Antarctica: Gondwana break-up volcanism; subduction-related volcanism; post-subduction, slab-window volcanism; and continental extension-related volcanism. A paper on the volcanology and eruptive palaeoenvironments is followed by one on the petrology and origin of magma for each tectonic setting and Antarctic region. The sixth section presents the tephra record from both marine and ice sediment cores. The seventh section details active volcanism, defined as any volcano that has erupted during the Holocene, for the different tectonic settings. Recommendations for future studies are given, as well as hazard and risk assessments for active volcanism.

The papers present in-depth syntheses of Antarctic volcanism. They include geographical maps, comprehensive tables of geochemical data and isotopic ages, geophysical information, and some stunning aerial and *in-situ* photographs, all excellently reproduced. Each paper ends with an extensive source reference list. This book is not a 'light read', nor does it intend to be. Its overall objective is to review and assess all aspects of Antarctic volcanism of the last 200 million years. Being the first volume devoted entirely to Antarctic volcanism in 30 years, it aims to review 30 years of unpublished knowledge from large datasets and observations. It purports to be the first comprehensive review of volcanism in Antarctica from 200 million years ago to the present and is intended to be *the* reference text on Antarctic volcanism for the coming decades.

The Introduction informs us that Antarctica has two major volcanic provinces, stemming from the break-up of Gondwana, which began *c*. 190 Ma: a mafic Large Igneous Province (LIP), which outcrops throughout the Transantarctic Mountains and in Dronning Maud Land, and with felsic outcrops throughout the Antarctic Peninsula. Subduction is active today only at the northern tip of the Antarctic Peninsula, and at a very slow rate. The West Antarctic Rift System (WARS), characterised by alkaline volcanism, developed during the Cenozoic. According to remote sensing studies, several volcanic centres may be active beneath the West Antarctic Ice Sheet (WAIS). The origins of the volcanism, such as mantle plumes and shallow thermal anomalies, are disputed, but all are categorised as part of a diffuse alkaline magmatic province (DAMP).

Antarctic volcanism, mainly confined to West Antarctica, has had widespread global effects, not least of which are driving mass extinctions, driving Antarctic climate and by extension world climate, and helping life to survive glacial episodes.

Here are a brief outlines of the contents of each section.

Section 1 Tectonic history and overview

This reviews the igneous activity resulting from the continental break-up, rifting and subduction processes as Gondwana drifted towards the South Pole and progressively disintegrated. The West Antarctic Rift System (WARS), which is one of the world's great continental rift zones comparable with the East African Rift and the Basin and Range province, developed during an extensional episode spanning the Late Cretaceous to Late Miocene. The continent was divided into the East and West Antarctic plates and the Transantarctic Mountains were uplifted. Chapter 1 provides insight into the lithospheric and tectonic processes that resulted in the present-day Antarctic continent, surrounded by spreading ocean ridges shown in a tectonic map of Antarctica. The next two chapters give a palaeoenvironmental overview of Antarctica volcanism, showing the great diversity of the major volcanic episodes over the last 200 million years, and an overview of the petrology of the Antarctic Plate, formed by *c*. 83 Ma; and discusses the intense debate centred on whether the primary sources of magmatism beneath the WARS are mantle plumes or subduction — related metasomatism, and whether OIB found throughout the rift is ancient or relatively recent. The last chapter in this section gives a brief summary of active volcanic systems in Antarctica and volcanic hazard assessments carried out.

Section 2 Gondwana break-up volcanism

Chapters 1 and 2 examine the volcanology and petrology of the Jurassic Ferrar Large Igneous Province in the Transantarctic Mountains. This province is geochemically unique among LIPs in significant Sr, Nd and Pb isotope enrichment. The next three chapters review the volcanology and petrology of the Jurassic-age Palmer Land Volcanic Group and Graham Land Volcanic Group on the Antarctic Peninsula, and of Dronning Maud Land, related to the break-up of Gondwana.

Section 3 Subduction-related volcanism

The first two chapters review the volcanology and petrology of the c. 1300 km long Antarctic Peninsula volcanic arc, which extends to the South Shetland Islands and is one of the major tectonic features of West Antarctica. It is thought to be a continental margin arc, erupted on the margin of Gondwana from Late Jurassic/Early Cretaceous through to Early Miocene. The following two chapters review the volcanology and petrology of Bransfield Strait and James Ross Island in the northern Antarctic Peninsula region, which is thought to contain more than 50 subaerial volcanoes and more than 100 submarine seamounts and volcanic ridges. Most are Plio-Pleistocene, erupted in diverse tectonic settings, some still unclear. This region is home to Deception Island volcano, the most prolific active volcano, and Mount Haddington, the largest volcano by volume in Antarctica. As elsewhere on the Antarctic Peninsula, most of the volcanism is subduction-related, erupted in a principally subglacial environment, but some is also marine and subaerial. Increased knowledge of the James Ross Island Volcanic Group has augmented our understanding of glaciovolcanism and of the configuration of the Antarctic Peninsula ice sheet. This purports to be the most detailed review of volcanoes in the northern Antarctic Peninsula region.

Section 4 Post-subduction, slab window volcanism
The two papers of this short section investigate post-subduction, slab-window volcanism, which is late Neogene and mostly glaciovolcanism, again on the Antarctic Peninsula.

Section 5 Continental-extension-related volcanism
This largest section consists of nine papers. It starts with mainly Eocene–Oligocene (52–18 Ma) glaciovolcanism in northern Victoria Land (subject of the first two chapters), probably largely triggered by the separation of Australia and Zealandia from Antarctica. This volcanism is part of the McMurdo Volcanic Group, consisting mostly of shield volcanoes, with a few relatively small stratovolcanoes, and is related to the WARS. The authors address the controversy about whether actively upwelling mantle splits continents, thus producing rift zones or whether upwelling mantle is passive owing to the splitting of continents during lithospheric stretching.

The Erebus Volcanic Province, subject of the following two chapters, also forms part of the McMurdo Volcanic Group within the Western Ross Supergroup and the WARS. It is the largest Neogene volcanic province in Antarctica. It consists of predominantly subaerial volcanoes dominated by large central volcanoes, of which Mount Erebus is the highest at 3794 m, with its three nested calderas and unique permanently convecting phonolite lava lake. These are shield volcanoes, which evolved into stratovolcanoes from 19 Ma to the present, and are so large they have sunk more than 2 km into the underlying lithosphere.

The next two chapters focus on Mount Early and Sheridan Bluff, two Early Miocene volcanoes exposed in East Antarctic. Although they form part of the McMurdo Volcanic Group and are therefore part of the Western Ross Supergroup, they are more than 1,000 km distant from other volcanoes, and it seems with a distinct origin to the WARS.

The next two papers are an update of the last major review — written 30 years ago — of the volcanology and geochronology of Marie Byrd Land (MBL) and Ellesworth Land. They focus on the 19 central volcanoes and numerous smaller ones in this remote region. These are the Marie Byrd Land Volcanic Group and date to the latest Eocene (36.6 Ma). The central volcanoes include some of the largest composite volcanoes on Earth. There is currently no access to the more than 90 hidden sub-ice sheet-volcanoes that have been documented by geophysical methods.

The final paper presents the volcanology and petrology of Gaussberg, a small, isolated nunatak situated on the coast of East Antarctica and composed entirely of lamproite pillow lava, erupted subglacially at 56±5 ka. Lamproite is a rare primitive ultrapotassic, mantle-derived magma, hence the petrological importance of Gaussberg despite its small size and isolated location, as it is one of only two type examples worldwide.

Section 6 Tephra record
This section begins with a paper on the marine record from drill cores, then continues with a paper on englacial tephras from ice cores from the East Antarctic ice-sheet. Glaciomarine sediment from the Southern Ocean contains primary tephra and volcanoclastic deposits produced mainly by explosive eruptions from Antarctic volcanoes. Data derived from marine cores extend the volcanological record back to 26 Ma. Marine tephra is an excellent chronological tool for the synchronisation and correlation of geological, palaeoclimatic and palaeoenvironmental records, enabling the reconstruction of climate changes and ice-sheet dynamics over time. Not only is Antarctic ice a significant archive of past climate, but it also provides information on past explosive volcanism, which it records particularly well; and chemical classification of ice- core tephra layers from the interior of the East Antarctic ice-sheet indicates the tectonic setting of the volcanic sources. The authors of this paper indicate a continuing scarcity of englacial tephra information for before 800 ka and for sectors facing the East Antarctic Atlantic and Indian Oceans, and anticipate a 1.5 myr extension of the ice-core tephra record by the International Partnership for Ice Core Science (IPICS) initiative.

Section 7 Active volcanism
This memoir fittingly ends with currently active volcanoes, and this section starts with a superb photograph of the permanent lava lake within the post-caldera summit cone on Mount Erebus. Indeed, each section begins with a spectacular photograph. The first of the five papers investigates one of the most active volcanoes in Antarctica — Deception Island in the South Shetland Islands — with 15 explosive eruptions over the past 200 years, the latest unrest in 2014–15. Future volcanic activity is therefore of concern for people working on or visiting the island, and intense research has been carried out over the last few decades, including hazard assessment. Hydrovolcanic activity (the combination of magmatic and hydrothermal activity) can result in highly explosive eruptions, even for small volumes of magma. Eruptive episodes in 1967, 1969 and 1970 destroyed or severely damaged the scientific bases on Deception Island. An eruption in the near future is expected.

We then move on to Mount Erebus on Ross Island in the Ross Sea near the western margin of the Transantarctic Mountains. This is just 35 km from McMurdo Station, the main US Antarctic research base. This paper presents five decades of scientific research into Erebus volcanism and is significant in that it not only includes geological, geophysical and geochemical observations, but also microbiological evidence. The tectonically active part of Mount Erebus, the Erebus volcano, is one of the rare currently active alkaline volcanic systems that gives insight into mantle melting processes and also biodiverse and endemic microbial communities. Strombolian activity is regular and bombs have been ejected from the persistent lava lake continuously since 1972 until the present. A warning of potential Antarctic volcanic activity causing a threat to the personnel of the international Antarctic science programme (Prof. John Smellie) was a science news item at the beginning of December 2021.

The third paper focuses on Mount Melbourne and Mount Rittman in Northern Victoria Land, quite close to three scientific stations. Both could potentially produce Plinian explosive activity in the near future. This could pose a serious hazard to large and distant communities.

Three volcanoes in Marie Byrd Land that have been active in the past 100 years — the focus of the next paper — could produce pyroclastic eruptions again in the near future. The deposition of volcanic ash could change the albedo of the WAIS and impact air-support operations at research stations. A potential subglacial eruption could destabilise an already unstable WAIS.

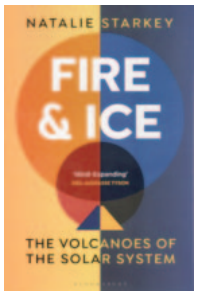
This section finishes with active subglacial volcanism in West Antarctica, concentrated along crustal boundaries and within the central WARS. At least 21 subglacial volcanic sites beneath the WAIS are known (to date), and are 'active' in the sense that they have interacted with the current WAIS. They can affect the ice dynamics by producing basal meltwater, which enhances ice flow and mass loss in coastal regions.

The book ends with a 12-page index.

Although expensive, for anyone seeking one book on Antarctic volcanism, this erudite, comprehensive, up-to-date book of more than 800 pages is of the highest standard and would be well worth the outlay. Each of the 31 papers contains in-depth information and is well illustrated, including some spectacular photography. In short, it is an excellent reference book for those interested in volcanology and Antarctica. Even if you know little about either, although challenging to read in places (you may need to refresh your memory of volcanism and petrology from OU modules!) there is a wealth of fascinating information for anyone with an interest in this subject.

Sue Graham, BA (Hons), BSc (Hons) Natural Sciences, MSc (Earth Sciences)

Book review



Starkey, Natalie 2021 *Fire and Ice:the Volcanoes of the Solar System*. London: Bloomsbury Sigma. (ISBN 978-1-4729-6036-8; 320pp; hardback £16.99; also available as an e-book 978-1-4729-6038-2)

The title of this book, and the information within it, are excellent. Anyone who reads it will gain a wealth of knowledge about our understanding of volcanoes on Earth, about volcanism in general — including the realisation that volcanics do not only consist of molten rock — and an up-to-date survey of volcanism on our Moon, on all the planets, and on many moons orbiting other planets in our Solar System.

The book has a Preface, 12 chapters, Acknowledgements and an Index.

It is a 'popular' science book, and it is for anyone to read who is fascinated by the wealth of new discoveries pouring out in academic and popular media publications about our Solar System. You will not be disappointed by the information presented and cannot but admire Dr Starkey's breadth of knowledge and ability to keep up with the pace of new information. Thus, the book fills an important niche and addresses a useful compilation that encompasses material not usually gathered together under one roof.

The 12 chapters address the definitions of volcanism and of cryovolcanism; the inner workings and sources of heat in the various planets and moons throughout our Solar System; the varied nature of volcanism and of cryovolcanism, and their output in rock or ice, and their chemistries; and the growing number of moons in our Solar System that could possibility harbour some form of life. Dr Starkey describes and explains these subjects, first in general, then in more detailed chapters addressing each topic, and then presents a survey of volcanism and of cryovolcanism around the Solar System from Mercury to the Asteroid Belt, including the Moon and many moons orbiting the planets.

However, as an academic editor and a geologist I have misgivings about the book's style and production. *I do not mean what follows to discourage anyone from reading this book!* But I do criticise the publisher, Bloomsbury, for seriously letting down its author.

The book lacks any citations, references or notes to the sources for the statements and information presented. Even given that the book is meant for a 'general' readership, there is no reason for leaving out even a general reading list of books, journal papers and on-line articles to back up the facts, statements, hypotheses, interpretations and conclusions declared in the book; and to provide at least a starting point for readers to be able follow up and explore further. The reading public — and certainly those who are interested in the subject matter of this book and likely to read it — deserves such academic accoutrements, which are by no means eschewed by 'general' readers as unnecessary.

As an editor I think the book is poorly written — especially in phraseology — and frequently over-wordy. The main text — from page 9 to page 309 — is frequently repetitious. Instead of 300 pages it could be easily reduced to 250 pages with no loss of information. There are numerous unnecessarily wordy constructions; an apparent compunction to repeat details already given or explained; and use of multi-worded modifiers of sentence main subjects, which could easily have been expressed in one or two words.

In addition, there a throw-away phrases and sentences that say nothing — they impart no further information and they add nothing. Examples include: "You may be surprised to learn…"; "You may be wondering…";"The thing about [x] is …"; "Yes, that's right, …"; and "…as we have learnt earlier, …" or "…as we've seen many times already".. See for example page 123, where "As we saw…", "As we've seen…" and "As we saw previously …" all occur within a few lines of each other.

There are several factual errors and inconsistencies; also grammatical and lexicographic errors. For example, throughout the book the word 'allow' is used (with only a few exceptions) when the author means 'enables', 'causes' or 'means'. Also throughout the book, the word 'further' is used exclusively when distance is meant, a nuance in meaning that seems to be ignored.

There are inconsistencies. For example:

- "Hawai'i" and "Hawaii" (both in different chapters and within the same chapter).
- 450˚C is 840˚F (p130) is later 842˚F (p132)

And there are curious errors. A few examples include:

- "Olympus Mons volcano on Mars stands nearly 25,000 metres (72,000 feet) high…", then "…Olympus Mons, which at 25,000 metres (82,000 feet)…" (both p38).
- We are told that the VEI relative measure of the explosiveness of volcanic eruptions … goes from 0 to 8" (p53), but then that "These types of volcanoes are classified by their size and magnitude, having an eruption history that measures VEI 8 or greater" (p66); and that because LIPs erupted "over 10,000 cubic

kilometres (2,400 cubic miles) of lava, [it gives them] a magnitude of over 9 on the VEI scale…" (p70).
• "Tambora was the most powerful eruption in human history…" (p61), then "However, despite Krakatoa being the most powerful eruption in recorded human history…". [Tambora erupted in 1815, Krakatoa in 1883, both within human recorded history.]
• Io, one of Jupiter's moons, is included as a planet on page 80.
• "data is" (p174), "Earth provides the only data point " (p212), and "(fewer data leads to worse statistics)" (p253)
• "The plume materials that are energetically pushed into space at speeds of 400 metres (1,312 miles [sic]) per second, overcoming Enceladus' gravity end up forming the E-ring [of Saturn]" (p284). [I venture to suggest: "The plume materials are energetically pushed into space at speeds of 400 metres (1,312 feet) per second, overcome Enceladus' gravity, and form the E-ring."]
• "the Earth's core sits at around 5,5,000[sic]–7,000˚C (9,032–12,632˚F) (p182).
• "The last fifty years has revealed" (p307)
• "even contain the raw ingredients and conditions to support potential life" (p307) It is the verb 'support' that needs the modifier, not the noun 'life', so it should be "even contain the raw ingredients and conditions to potentially support life."

Type-setting errors include:
• "eruptions at Io" [? 'on Io'] (p87)
• "its more explosive and fierier [sic] past" (p94)

There are confusing sections:
• Mauna Loa is "just 4,207 metres (13,802 feet) above sea level" (p38). It is therefore obviously considerably higher if measured from the sea bed; on Earth "The spreading ridge is characterised by the highest mountains" (p100); and "some parts [meaning the highest] of the ridge [rise] to 4,500 metres (14,600 feet) above the seafloor" (p105). Mauna Loa's 4,207 metres are 297 metres lower than the ridge's 4,500. Therefore, surely Mauna Loa is higher *from the seafloor*.
• If spreading ocean ridges on Earth are described as all around the globe, and their hydrothermal vents are all along the spreading ridges, then why are the chemical ecosystems created by the vents so "rare and unusual" (p142)?
• Page 211 refers to "Venus, despite being closer to the Sun and having a hotter surface, cooled down much more quickly [than the Earth]" (p211). But, — again comparing Venus and Earth, "Its [meaning Venus's] slightly slower rate of cooling meant …" (p212).
• The Moon's "lower gravity results in taller lava flows…" (p228), then, curiously, that on the Moon "lack [*sic*] of gravity, which allows [*sic*] lava to spread out over great distances instead building up to form elevated features" (p230).
There are nine pages (pp255–63) describing how different Venus looks and how differently its geology behaves compared to the Earth, followed by "Venus is a planet much like our own" (p264).
• The basalt of Olympus Mons on Mars is "formed from the very same material that produces many of Earth's volcanoes", then eight lines later that "Mars' basaltic dust contains more iron than the equivalent basalt on Earth…" Surely this fact means that the two basalts are *different*.
• There is no explanation of how we know that the meteorite called 'Black Beauty', found in the Sahara Desert in 2011, is from Mars (p274).We are told that "Around 2005, NASA's Cassini spacecraft photographed plumes … on Enceladus" (p282) The lack of clarity is in the verb and subject agreement: Do we not know the actual year? Did Cassini take these photographs in several places on Enceladus? Or did Cassini take the photographs *during* 2005?
• "Cassini's buddy, the Huygens lander, hitched a ride from Earth to Titan, before being released by the orbiter to venture down to the surface and punch through Titan's thick atmosphere" (p288). Surely this word order is incorrect? Perhaps "After reaching Titan, Cassini's attached Huygens lander was released, punched through the thick atmosphere and landed on the surface" is the correct word order and less twee — and is also 11 words fewer.

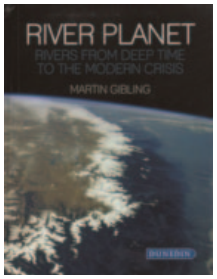
Throughout the text I found numerous unnecessary passages and whole paragraphs that could be deleted without loss of information; and numerous sentences that could be reworded using half to two-thirds as many words to express the same information.

To conclude, the text of *Fire and Ice* seems to this reviewer to read more like a first draft. It seems intermittently, and often hastily, written. My purpose in pointing out such avoidable errors is not to belittle Dr Starkey, but rather a plea to publishers to use competent proofreaders and editors. As it stands, the text of Fire and Ice is longer than it needs to be, and could have been easily corrected and shortened.

With the successful launch and safe deployment of the Webb Telescope (JWST) in 2022 much new data will be discovered about space, including about our own Solar System's planets and about exoplanets, as well as about the origins of the universe. I look forward to a second edition of Dr Starkey's commendable book.

— Dr David M. Jones. OUGS Proceedings Editor

Book review



Gibling, Martin 2021 *River Planet: Rivers from Deep Time to the Modern Crisis*. Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-099-4, eISBN 978-1-78046-658-3; i-xv +222pp; hardback £28.00)

Prof. Gibling, Emeritus of the Dept of Earth and Environmental Sciences at Dalhousie University has written a world geography and geology of rivers. He starts with the first drop of water on Earth and flows through the ages right down to the present day.

In five Parts , each with several chapters, he describes the advent of water on the Earth in 'deep time' and continues through the development of rivers as water collected and began to shape the landscape, to ancient times and all the way to modern time as humans began to settle by, interfere with, redirect, use, pollute and even begin to restore rivers.

Rivers can be likened to the circulatory system of the living Earth. They provide not just water to quench thirsty plants, animals and humans, but also provide depositories and habitats for resources, sustenance, growing, transportation and communication, exploration, carrying away waste, and climate regulation — in short they are vital to the Earth and everything that lives on it.

Part 1 begins in'deep time'. 'Rivers and Geological time' describes the geological study of rivers and how the earliest geologists examining their sediments and deposition layers began to realise the true age of the Earth. With a clear narrative and numerous colour diagrams and photographs Prof. Gibling explains how rivers work, the shapes they take and why, and the terminology that geographers and geologists use to name river forms from their sources to the deltas and seas into which they empty their waters. He shows examples of existing rivers and how their courses changed through time, how they collect water at their sources, and how they join, anastomose (branch), meander, braid, and fan into deltas; nor does he ignore the role of springs.

The earliest water on Earth has been dated in zircon crystals at 4.4 Ga, recorded in sediments of Western Australian conglomerates and sandstones, themselves 3 Ga old and including grains of zircon eroded from earlier rocks that had been transported in rivers. The section finishes with descriptions of the role of plants in 'bending and splitting' rivers — which he calls the Great Green Landscape Revolution. Archean and Proterozoic rivers flowed across empty lands, eroding rocks and sediments, and forming channels to be sure, but basically across flood plains. From the Ordovician onwards, however, the evolution of plant life and colonisation of the land began to create new types of sediments, such as peat, clays and the like, and began to change the nature of rivers and the sediments they eroded, carried and flowed through. Early animal life, feeding on plants had their effects as well.

Beginning Part 2, Chapter 4 describes the beginning of 'modern' rivers in the break-up of Pangea and the great rivers of Africa. One of the most interesting diagrams is a colour-coded horizontal bar-chart comparing the longevity of selected modern rivers on each continent that are still "broadly in their ancestral courses" (p38).

After discussing the great, 'ancestral' rivers of Africa, Chapter 5 does the same for Australia, New Zealand and Antarctica; Chapter 6 the 'young and restless' rivers of Asia; Chapter 7 the 'conflicted' rivers of Europe; Chapter 8 the 'reversing rivers of South America; and Chapter 9 the 'canyons and cataracts of North America. In these chapters there are astonishing palaeogeographical maps of each continent's rivers, one of my favourites being Figure 8.4 (p87) of the astonishing 15 km wide meander belt of the Paraguay River in South America.

Chapter 10 discusses the example of the ancient 'Amazon' of Canadian North America, a massive drainage from the western cordillera on the Pacific side right through what is now Canada. At least six major river systems flowed into the final 'great' river, flowing through the Hudson Bay Basin, out of the Hudson Strait, into a huge fanning delta, then into the Bell River between what are now north-eastern Canada and Greenland (Fig. 10.2, p102). Cenozoic ice sheets later destroyed the delta and the Bell River.

Part 3 is about how ice sculpts and changes rivers. Chapter 11 describes the great Palaeocene and Pliocene rivers of 'the north' and the effects of the Earth's five great ice ages on rivers: Proterozoic, Ordovician, Silurian, Devonian-Permian and finally the 2.5 Ma Pleistocene Ice Ages. And the most recent ice age leads into Chapter 12, describing the 'megaflood' in North America (and Siberia as a matter of fact) when the great western Corilleran, Laurentide, and Innuitian ice sheets of the north began to melt *c.* 8000 years ago and the great ice dam was breached to flood North America, leaving us not only the great rivers through the middle of the continent, but also the Great Lakes, the Finger Lakes and great waterfalls, as well as countless small lakes throughout northern Canada. (I had a Canadian colleague at Cornell University, where I taught, who spent a summer working for the Canadian government — his job was to be piloted over northern Canada, maps in hand, to name lakes!)

Chapter 13 describes rivers drowned by the sea. Examples abound: several in Arctic Canada, the Molengraaff River of Southeast Asia, the former Channel River of western Europe, and chalk land rivers in England.

Part 4 is devoted to human influences on rivers. These are perhaps the most fascinating chapters to me as an archaeologist. Rivers were of major importance from the dawn of humans, if for no other reason as their source of drinking water, but also no doubt acting as barriers in human evolutionary terms, when there were multiple contemporary hominid species competing for existence. With the advent of farming, rivers became the vital arteries of human civilisations. Every early civilisation in the world adhered to, was influenced in its development by, was controlled by, fed by a river, and used rivers to expand, communicate, trade and explore. Two more favourite figures in Gibling's book are Figure 14.2 (p135), showing the increasing influence of rivers on humans and of humans on rivers from *c.* 15 000 years ago to the present; and the wonderful schematic cartoon of Figure 14.5 (p137, drawn by Meredith Sadler) showing "the range of anthropogenic influences on river systems". (Archaeologically this chapter covers familiar ground to me, but I was a little disappointed not to see a mention of ancient Nazca use of underground desert rivers in not only one of the oldest civilisations of the New World, but also the driest desert in the world.)

To explore some of these themes in more detail, Chapter 16 is a fascinating history of Chinese engineering of the Yellow River from the earliest Chinese emperors from Yü the Great 4000 years ago, to Confucian times (Confucius b. 551 BC) to modern times.

And finally, this example of river engineering leads into Part 5, all about 'Engineered Rivers. Here we enter more disturbing chapters describing 'Dead and Wounded Rivers' (Chapter 17), in which humans threaten their own livelihoods by overusing and taking undue care in 'controlling' their rivers. Examples inevitably concentrate on dams and polution: in Romania (the R. Sebes); in North America (the effect of 'hydraulic mining' in the Sierra and the flooding of Hetch-Hetchy Valley, California, and the Hoover Dam); in China (the Three Gorges Dam); and in India (the 'indigo river' — the Luni — created by the cotton mills of Pali). You no doubt can come up with one of your own examples wherever you live!

Chapter 18, sadly, continues this story, giving examples in Colorado (the Roaring River created by the collapse of Lawn Lake Dam);in Egypt (the flooding created by building the High Aswan Dam — anathema to archaeologists!); in Zambia and Zimbabwe (the Kariba damming of the R. Zambezi); and of course the great Glen Canyon Dam in Arizona, not to mention the several dams along the Colorado River (The Parker, Hoover, Grand Valley and Granby dams).

Chapter 19 discusses the mixed opinions and multiple effects on the land 'between the dams' along the Saskatchewan in northern Canada. This river is the remnant of the great Bell River 'Amazon' of Pleistocene North America.

Chapter 20 turns to look at the other side of the coin and describes examples of how peoples used rivers with more respect and made their agriculture flourish 'Without Spoiling the Land', both ancient and modern.

The remaining two chapters are more about 'fighting back'. Chapter 21 is a curious chapter about London's buried rivers. Like many modern 'western' cities, the rivers get channeled underground. We know about many only from references to them in medieval or earlier sources. I was pleased, therefore to see Gibling's Figure 21.2 (p190) of the River Thames and its tributaries, most of them now underground.

As an archaeologist for the London Department of Urban Archaeology in the 1970s I directed an excavation under buildings being cleared for development, in which the Roman layers included timber revetments that the Romans had erected to channel the Walbrook Stream. That must have been the beginning of its 'disappearance'. Also from my own reading, the Moorish medieval kingdom of Granada provides a classic example of Moorish water engineering in the creation of terraced and watered lands all around the city and in its numerous delightful interior courtyards with trickling water channels to feed the fruits trees, herbs and flowers. In the mid-19th century a major source of the city's water was, much to the disgust of many, hidden away by the tunneling and 'vaulting'of the River Darro and its tributaries in an attempt to clean up the city. Residents said it killed the heart of their city. And I read an article online a few years ago about the rediscovery of San Francisco's streams, mostly unknown to most residents except those whose basements flood every year because their houses are over one of them! An urban movement in San Francisco is in fact uncovering some of these streams to create miniature nature areas along them.

Similarly, New Yorkers are doing work to clean up the Hudson River, as are Londoners to clean up the River Thames. Gibling even describes the 'blowing up of a dam' by farmers in Iceland in1970 in protest against the damming of the Laxá below Lake Myvatn; and the cleaning up and preservation of the Sackville River in Nova Scotia, a region of Canada with a population of less than a million, but which boasts 80 river conservation groups!

Gibling ends his book with a poignant Epilogue about his 'own' river, the River Barle on Exmoor, Devon, which I will leave for you to seek out and read.

A short Glossary, three pages of Further Reading, eight pages of detailed source notes and references, and an eight-page Index finish the book.

Prof. Gibling is a well-read man. His book is peppered with literary references to books and titles that allude to or have a relevance to rivers he is discussing. From biblical Noah (who comes along in Chapter 12) to modern novels and newspaper articles his writing seems light and easy while being dedicated and informative.

The palaeogeographical maps in this book are astounding examples of geological and geographical reconstruction, which I regard as highlights throughout the book.

The book is produced on high-stock, laminated paper, which makes the colour figures crisp and clear.

— David M. Jones, OUGS Proceedings Editor

Book review

Mann, Michael E. 2021 *The New Climate War: the Fight to Take Back Our Planet.* London: Scribe (ISBN 078-1-91334-868-7, eISBN 978-1-92593-886-9; I–xi + 351pp; paperback £16.99)

This is a thorough, honest and hard-hitting book by a scientist who has been warning us for decades about the dangers of what we are doing to our planet.

Yes, Climate Change again. Or more accurately, Climate Change Crisis.

Despite several international conferences and many pledges the situation has got worse. There is no denying it and we cannot escape from it.

Michael Mann, sometimes known as 'the hockey stick guy', is, in case you were unaware, a geophysicist and climatologist of international standing, Distinguished Professor of Atmospheric Science and Director of the Earth System Science Center at Pennsylvania State University.

He knows what he is writing about.

In essence, this book has two messages: 1. That the damage we have already done to our plant, despite continued warnings, has without doubt been done; and 2. That there are still things we can do to limit the damage and start back towards rectifying it.

There are nine chapters. Their titles epitomise what each is about. In each of them Mann works methodically through the disingenuous efforts of many people and organisations to deny, belittle, circumvent, 'disprove' or just plain ignore the growing crisis. Every chapter is backed up with hundreds of notes and references to his sources and data. His Notes section is 64 pages (pp273–336).

His Introduction starts with Al Gore's mid-1990s warning so carefully presented in his address *An Inconvenient Truth*. But this opening reference follows a long quotation beginning, "There is general scientific agreement that the most likely manner in which mankind is influencing the global climate is through carbon dioxide release from the burning of fossil fuels… There are some potentially catastrophic events that must be considered." Gore? No! These words were written in the 1970s by James F. Black, senior scientist at ExxonMobile. The documents are in the company's archives.

Chapter 1 'The Architects of Misinformation and Misdirections', begins with the advocates of denying that anything is wrong by disseminating various lines of information to tell us that the information the scientists are telling us is not true, is over-blown, is an attempt to tell us that things are happening and being done in our names that are scare-mongering. All of which are not true. Scientists have been warning us since the 1970s that our use of fossil fuels is producing a toxic atmosphere on Earth; and that our failure to recognise that our use of the Earth's resources is exorbitant and wasteful, and is polluting our environment. Mann refers to Rachel Carson's fight against the use of DDT in *Silent Spring*, and the same treatment was given to her evidence. It was denied and dismissed, as a classic example of misinformation and misdirection. Their message is that there is no need to worry, it's OK, all the data are not in, all the data does not agree. So let's wait and see. We don't need to do anything just now.

In Chapter 2, 'The Climate Wars', Mann gives us a brief history of involvement with the growing evidence that what James Black, and others, were saying in the 1970s is true. He outlines his own research, that of many other scientists, and how it began to look as if their data, their graphs and predictions were correct. Through the 1980s the mounting evidence was becoming too undeniable for the likes of Exxon, Shell, British Petroleum, Chevron, the American Petroleum Institute and others, which led them in 1989 to form the Global Climate Coalition, whose efforts were unashamedly to disseminate in newspapers, public debates, fake scientific articles, and other means to tell the public that the science was uncertain, scientists' models were unreliable, the data too little and actually error-ridden, and that the role of 'natural variability' was too little known and unclear to reach the conclusions that scientists had already reached.

But into the 1990s, especially through advocates such as Al Gore and others, a substantial percentage of the public was beginning to become more aware and wonder what was really going on.

The early, breezy denial was begining to fail, so the deniers began to use different methods. They started to change their tactics, as 'deceivers', 'dissemblers', 'downplayers', 'deflectors', 'dividers', 'delayers', and 'doomers': the "D's.".

It began — Chapter 3 'The :Crying Indian" and the Birth of the Deflection Campaign' — with deflecting the blame. The producers of fossil fuels for our convenience and to power our civilisation were not the ones to blame. They were only giving the public what it wanted, what it asked for. They wrung their hands with innocence and put out the message that people want their product and that they were therefore obliged to supply it. The fossil fuel producers also pitted the various climate researchers against one another, fomenting and inflating any disagreements between scientists. There was no need for any collective effort to investigate the situation. The "Crying Indian" of the chapter title refers to an AmericanTV advert in which a Native American is shown picking up litter and pollution at a stream as a poignant tear trickles down his cheek. The implication is that he is on his own land, and the message was that it's *you* who are poluting your environment so it's up to *you* to clean it up.

These same deceptive methods were exactly those used by the tobacco companies through the 1950s and 1960s about the effects of smoking: we are only providing what you ask for; the evidence is unclear and uncertain.

Chapter 4, 'It's Your Fault', continues to emphasise these efforts by the fossil fuel organisations. They put out the concept of the 'personal carbon footprint'. Because they were beginning to realise that some of their efforts were being questioned, they stepped up the denial by deflecting and dissembling the argument onto the individual. If you're so worried about how much carbon dioxide you are producing, then *you* do something about it. We're just providers.

Campaigners and scientists sending their messages out and presenting the evidence were labelled as antisocial, as disruptors of society, as advocates of untrue misgivings and fomenters of public division. Among other points made by Mann in this chapter, he refers to politicians — examples, Donald Trump and Vladimir Putin — who simply 'deflected' everything as authoritarian figures by dismissing the evidence outright, and attacking scientists and climate research campaigners as involved in a conspiracy to deceive 'the people'. The deniers and dissemblers justify their

claims by saying all these research people are hypocrites, because they also fly in airplanes, drive cars, eat meat…

Chapter 5, 'Put a Price on It. *Or Not*', describes the cost of fossil fuels, their production and what the public is charged for it. Under the argument that the producers only give the public what it wants, follows the argument that the costs can be deflected and delayed by carbon credits. We're OK. If we get others to take the cost for us, we don't have to clean up our act just yet. And besides, everyone wants to raise their standard of living so we can't deny the people of 'the Third World' countries their chance to do so. We've got to provide them with the energy they need to do so.

In addition, because production is cheaper for 'conventional' energy sources, fossil fuel energy providers call it unfair to give more expensive energy source producers subsidies to level the playing field. They put out propaganda to discredit renewable energies, claiming that they were unviable as an alternative source of energy. The claim is that these renewable energy sources are a false solution.That they won't work, That they take jobs away from ordinary, hard-working citizens in the fossil fuel industry.

Chapter 7, 'The Non-Solution Solution', can be summarised as the argument that there is really nothing that *can* be done. That the energy already provided is 'not so bad'. Non-solution solutionists put out the message that there is 'clean coal', that the use of natural gas is not as bad, and provides a 'bridge fuel' to get us along until we can solve any problems through human ingenuity. We've always managed before. We can do it again. But in the mean time …

Some in this camp even put out dreams about untold surges of energy, minerals and other resources deep beneath the world's oceans, on the Moon, on asteroids — if only we were given license to mine it/them, given 'government' money to invent what we need to do so. In essence, further denial of the reality of what is actually happening to the planet now, even if it is admitted that some damage has been done already, and believing that we can engineer our way out of any problem with technology. In the mean time, they delay.

Basically, these advocates are saying that we should just carry on as we are.

Chapter 8, 'The Truth is Bad Enough', is about the 'doomers'. It's all got so bad already, and there is nothing we can do about it. We are doomed. Basically, doomers just don't care. I'm all right Jack, so I just carry on with my life quietly and don't bother others. But to ease their consciences, doomers claim that scientists and climate campaigners are overstating the case. Like outright deniers of the evidence, such beliefs give one the right to do nothing, and justifies their belief that the evidence is not really so clear anyway.

The tactics and positions taken by deceivers, dissemblers, downplayers, deflectors, dividers, delayers, and doomers lead down the same road: delay and inaction. Even the best pledges by the most powerful governments around the world have, in World Meeting after World Meeting, not been met. There are always fine words, good intention, and then delays. It has been going on for decades.

But Prof. Mann is no defeatist, nor does he have much time for all the "D's." In Chapter 9, 'Meeting the Challenge', he provides a straight-talking summing up of where we are now. There is no denying that we have done a huge amount of damage to Earth's environments and to its atmosphere. Some points have been reached that cannot be easily or soon reversed.

Mann states, "Despite the challenges detailed in this book, I am cautiously optimistic".

Mann is a realist, and definitely not a defeatist. Unprecedented, extreme weather disasters have opened many more people's eyes. The COVID-19 pandemic has taught us key lessons about just how vulnerable we are. And an awareness of environmental issues has risen sharply and become the campaign of younger generations, alongside those of us who have been providing evidence of the damage being done. We have confronted the D's and have weakened their grip. Poles now show that a much larger percentage of the world's population is at least more aware of what is going, and it is almost impossible to keep information from them. The availability of online and social media sources, short of pulling the plug on every citizen's electricity supply and mobile phone charger, cannot keep people from finding out eventually what's going on. If big governments are going to hold COP meetings and make pledges, they are sure to shout to us what they are saying and pledging. They shout it at us through their news and propaganda output. Even if some of it is conveniently filtered to make one's own nation and government look like the good guy, we can hold them to account. We are not uninformed and certainly not stupid. We can take action.

Here is the essence of Michael Mann's proposals, his 'battle plan':

1. "Disregard the Doomsayers". Ignore them if need be.
2. "A Child Shall Lead Them'. Younger citizens of the world hold a moral authority and their message is crystal clear. They want a world they can live in. It is their world too, and they will have to live in this world after us. If we fail to listen to them the blame and shame are on us.
3. "Educate, Educate, Educate". Forget the most adamant, unmovable deniers. They are in the minority now. We are scientists, intelligent and informed people. We have the knowledge and, given the example of the rapidity with which the world's scientists pooled and shared their knowledge to develop COVID vaccines in record time, we should be convinced at how cooperative we can actually be. This outcome was not simply an engineered solution to an immediate problem. It was a lesson and revelation of what science and knowledge are, and about what can be done in the right hands and with the backing of everyone.
4. "Changing the System Requires Systematic Change". We need policies that incentivise the move away from fossil fuel use to create a cleaner and greener global economy. So-called leaders who continue to deny, delay and resist this call should be removed from office.

If all this sounds idealistic, then what is your answer? It is time to cease wasting our time pointing fingers, blaming and trying to shift responsibility. The responsibility is all of ours.

There is also a useful Index at the end of the book, so that after you have read it, you can find your way back to passages and sections you want to read again and use in your own writing.

— David M. Jones, OUGS Proceedings Editor

Book review

Gordon, Helen 2021 *Notes from Deep Time: a Journey through Our Past and Future Worlds*. London: Profile Books Ltd (ISBN ISBN 978-1-78816-163-3, eISBN 978-1-78283-504-2; 322pp; hardback £20.00, paperback £9.99)

This book caught my attention when reading a newspaper reviewer' description of it as "a dazzling book" deciphering the history of deep time of our planet. Given the immensity of 'deep time', it would seem, that 276 pages of text was a canter through history, jumping from the present into the deep past, and to what the future might hold: how humans are affecting what that future might be. The author has clearly done an assiduous amount of research, interviewed world-ranked specialists in many earth science fields, travelled widely in the UK, Europe, and much farther afield, reflected by 20 pages referencing her sources, plus three pages of recommended further reading. It seems like the author's narrative was a very small tip of an iceberg.

The book opens with the author's interest in what lies below our feet by a building site excavation in East London, which she describes as a "layered pink white and yellow angel cake", and about which she learns that the upper layers are the deposits from the Pleistocene Epoch (2 Ma) overlying London Clay (55 Ma) and older layers below. Gordon poses two questions: "What will we leave behind?", and "What will survive us?"

With that introduction, the reader is taken to Copenhagen and its Greenland Ice Core Archive, curated by Prof. Jorgen Steffenson, and what its layers tell us, going back through more than 60 000 years of evidence.

In the more recent past, in the Holocene *(c.* 11 700 years ago) there is evidence of rapid temperature change at a time when farmers were succeeding hunter-gatherers. The reasons for such variations are uncertain, but today's man-made climate change leads Prof. Steffenson to state,"My greatest fear is that all of a sudden it will stop raining where we want it to rain, and start to rain where we don't need it to. That's my biggest fear: that the change will be so sudden that farmers can't adapt."

But what has that to do with the Earth's geological history?

The reader is next taken to Siccar Point and James Hutton's challenge to Bishop Ussher's 6000-year calculation of the Earth's age, to the tentative 75 000 years proposed by Comte de Buffon, and Hutton's realisation that Earth's processes are endless cycles of destruction and repair, and must mean that vast periods of time were involved; then to refinements of these time periods by Charles Lyell and by Charles Darwin, and, finally, to modern day radiometric dating of 4.5 billion years, a number that would have been unthinkable to Hutton and his contemporaries and successors. Gordon then briefly describes even greater dates attributed to slivers of meteorites, and the efforts of the International Commission on Stratigraphy (ICS) and the interplay of science and politics in the establishment of a settled International Stratigraphic Chart of stratigraphic ages to measure 'deep time'.

After Copenhagen, Siccar Point, the San Bernadino Mountains in California and the San Andreas Fault — with an aside on non-scientific prediction methods for the next 'big one' — Gordon returns to the UK and the chalk of the Chilterns.

After this hasty treatment of such huge subjects, there is an excellent description of Chilterns geology, with observations on how the population of the region has increased and the consequent pressures on transport, building HS2 and the impact on the region's water reserves held in the chalk aquifer. Gordon gives a speculative description of a view from the North Downs over London and imagines the blueness as though the old Cretaceous Ocean has returned to fill the London Basin and submerge the city after the ice sheets melt and sea level rises.

From water we are taken to fire. Gordon takes us to Campi Flegrei near Vesuvius, where a population of more than half a million people live in a red zone that would be overwhelmed and destroyed by the next eruption. She gives a sketch of the study of volcanoes, and the difficulties of predicting eruptions. She poses the question as to why the residents choose to live near such risk. They answer with a fatalistic shrug, saying that residents had always lived there.

Gordon next digresses to a discussion of the world of fossilised plants and creatures, describes the life and impact of Mary Anning (and the recent film about her — *Ammonite*), contrasting Anning's recent fame and recognition to the less-than-substantial recognition she received in her own time. Gordon also compares these issues with modern-day loss of female talent when they train as geoscientists, but are not fully not fully represented in academia and private sector employment.

The narrative perks up with an expansive description of the Devonian, described by Gordon "…as the moment in the history of our planet when the world first became to look like our world. It is the time when first the plants and then the animals began to move in large numbers from the waters to the land. A great greening of hitherto bare rocks, the first footsteps impressed in the mud of some long-vanished swamp or shoreline"

Gordon describes the life of early plants; the first forests and their fossil record; the creation of the Earth's soil; the forest's detritus and tree roots breaking down rocks to release minerals and nutrients to create richer, more stable soils; changing rates of erosion; trees altering the water cycle; and the conditions that led marine creatures to find their way through sand, mud and reeds to the land.

Next we are taken to dinosaurs and the modern-day popularity triggered by the film *Jurassic Park*, and to fictional encounters between Tyrannosaurs and people. Aside from this fictional world, Gordon gives a detailed analysis of palaeontological explorations in the USA, especially at the Cleveland-Lloyd Dinosaur Quarry, Utah. She deplores the loss to science of much material, because it finds its way into private hands rather than to scientists for research. Gordon suggests that perhaps dinosaur popularity is because at one time they ruled the Earth, but then suddenly did not after a meteorite impact destroyed their environment.

Next Gordon delves into the research by palaeobiologists to explore the colouring of long-dead creatures, and what 'Urban Geology' tells us about our surroundings from the work popularised by Eric Robinson, and by others since, about the Anthropocene.

In these final chapters, the reader is taken back to Copenhagen, to the evidence of the Ice Core Archive, and how human influences might be seen to cause "…modified global cycles of carbon and nitrogen; rates of extinction well above background levels; enhanced erosion; a spike in artificial radionuclides caused by thermonuclear weapons tests in the mid-twentieth century".

Gordon concludes that, "Viewed through the lens of the Anthropocene humans become a geological force comparable with the immense volcanic eruptions such as the Campanian Ignimbrite, or the variation in the Earth's orbit that drives glacial cycles."

She does not express a great deal of optimism for the deep time of the future. After discussion of what the Anthropocene is, when it started (if it has), whether it is a 'real' geological concept or an aspect of geography, Gordon takes us to one of the most pressing issues of our time: the need to securely and safely dispose of high-level nuclear waste for at least 100 000 years hence, and maybe a million years, before the waste is deemed to be no longer hazardous to human life. We are taken to Oukalo, Finland, to a project that, when completed, will store some 2800 canisters of spent fuel in a 60–70 km network of tunnels, which no one alive now will have seen; then to the Cigeo Project in north-eastern France, where much emphasis is being placed on how our descendants 100 000 years or more hence will know about the dangers of what is underground at such repositories.

There is a thought-provoking discussion about keeping the memory of this danger alive: Gordon suggests that maintaining knowledge from generation to generation of scientists could create a small elite group that might not necessarily work for the common good; that warnings and danger signs now may mean nothing to a curious archaeologist thousands of years hence; and that today's languages could be incomprehensible in the near future, never mind thousands of years hence. Gordon even surmises that a universal sense of alarm and fear captured by Edvard Munch's *The Scream* might still have relevance for the future. She suggests that the extensive opposition to such projects, especially to Cigeo, may itself keep the memory of this danger alive.

So, in summary, Helen Gordon opens with a warning from the evidence of the recent past. She explores aspects of the Earth's cycles from deep time to the present, and describes our human impact on aspects of the Earth's cycles that could affect the future. Between these opening and closing bookends she ranges through Europe and America in a narrative that reads like a script for a documentary or travelogue for 'popular science'. But throughout, I do not think Gordon provides enough detail about many subjects to enable the reader to fully understand — not without exploring the voluminous cross-references and extensive bibliography given at the end of the book. I do not fault Gordon's writing skill, but do not think 276 pages sufficient to cover the breadth of the book's themes.

— Martin Keegan

Book review

Lomax, Dean R. 2021 *Locked in Time: Animal Behavior Unearthed in 50 Extraordinary Fossil*s. New York: Columbia University Press (ISBN 978-0-23119-728-1; 286pp; hardback $29.95 / £25.00)

This is a gem of a book!

Dr Dean Lomax (visiting scientist at the University of Manchester), sometimes known as 'the Ichthyosaur expert', has written a page-turning book describing 50 truly extraordinary, not to say astonishing, examples of fossilisation and preservation, each of which shows a different aspect of an ancient creature's behaviour.

The book is enhanced by 50 excellent single and double-page spreads of illustrations by paleontological artist Bob Nicholls. The production of Nicholls' illustrations in half-tone is perhaps a deliberate way of showing just how illusive the preservation of 'behaviour' is. And in any case, many of the examples took place under the murky waters of ancient toxic lakes, or within shadowy underground dwellings. In addition, there are 45 half-tone figures showing many of the fossils themselves, and their excavation and analyses.

The dust-jacket image is also by Nicholls. And there is a clever frontispiece by Ray Troll of a 'pile' of a chronological cartoon of the geologic time periods.

Lomax and Nicholls divide the book into five sections: 'Sex' (9 cases), 'Parental Care and Communities' (10 cases), 'Moving and Making Homes' (11 cases), 'Fighting, Biting, and Feeding' (11 cases), and 'Unusual Happenings' (9 cases).

The detective work in finding, analysing the evidence and reaching conclusions about the behaviour in which each creature, pair or group was engaged in is truly fascinating, not to say both reasoned and intuitive.

Following an Introduction subtitled 'Unlocking the Prehistoric World', the examples range in time from the Cambrian to the Holocene. Lomax's narrative style is easy and clear. There is no doubt about what is actually there to see in the fossil and what has been interpreted and concluded about the animal's behaviour from the evidence. There is no hyperbole — just the facts and the story of what happened. And personally, I very much like Lomax's sense of humour and fun, with chapter titles like 'Shell-Shocked Mating Turtles', 'Magalodon Nursery', 'Sitting on Jurassic Bay', Cracking Case of the Bone-Crushing Dogs', and 'Could It Be Dinosaur Pee?' — to choose one from each section.

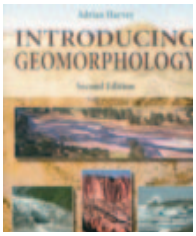
The are many 'firsts' here, such as then oldest examples of parental care (Cambrian *Fuxianhuia*, *Kunminggella* and *Waptia* associations with mothers, eggs and embryos), or the earliest record of a mating fossil pair (165 Ma Jurassic froghoppers). There is sex, fighting, invasion, co-opting others' dwellings, meals just before death, nursery and sibling care, migration, scavenging, crawling before being smothered, mass stranding, entrapment in amber, mass suicide (unintended of course), and even farting and peeing!

Both author and artist give their generous acknowledgements to the many people who made their collaboration possible. The book ends with a 20-page section of further reading, chapter by chapter, with Lomax's sources; and an Index.

This book is a wonderful and fruitful collaboration between a palaeontologist and behavioural scientist, and a palaeontologist and artist. It goes well beyond the identification and naming of ancient animals. It tells us what we really want to know about ancient life.

— David M. Jones, OUGS Proceedings Editor

Book review



Harvey, Adrian 2022 *Introducing Geomorphology* (2nd edn). Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-103-8, eISBN 978-1-78046-673-6; i–xii + 146pp; paperback £9.99)

This second edition of Adrian Harvey's *Introducing Geomorphology* (originally published in 2012) is somewhat expanded, to 246pp compared to the first edition's 124pp; and its original subtitle of *A guide to Landforms and Processes* has been dropped.

The new book's form is similar to the original, but of course, after nine years there are changes and updates. As was the intention of its predecessor, the book is aimed at a general readership, at readers with a level of general geological knowledge, perhaps studying geology or physical geography at A Level or as an undergraduate. The book's material will be familiar to OU students who have completed the second-level geology course. This second edition sits well with other volumes in Dunedin's impressive range of titles and geological-geographical topics in this growing series of introductory books.

Geomorphology is the study of landforms, the processes that form them and the chronology of their formation; plus human impact on the land.

The book is organised into six chapters, each with several subsections. The chapter and subsection titles cover precisely what their titles describe. Concepts, processes and terminology peppers the text in blue, reflecting the Glossary entries at the end of the book. Curiously, chapter '1' is followed by a section with an equally weighted heading, labelled '1.5' — this is new material. The 'six' chapters are:

1 'Introduction to geomorphology'. This chapter explains the basic terminology: landforms, space scales, time scales, 'fundamental driving forces' in geomorphology, and Internal (geological) and External (climatic) forces that create the landscape we see.

1.5 'Different approaches to the study of geomorphology' defines and describes two approaches: 'evolutionary geomorphology' and 'process geomorphology'; and the data sources for geomorphological studies.

2 'Global-scale geomorphology' discusses plate tectonics, the ocean floor, continent tall landforms, global climate, effects of climate on landforms, the Quaternary glaciations, and other Pleistocene climatic changes, Quaternary sea levels, and the global interplay of tectonics and climate

3 'Regional-scale geomorphology' amplifies many of these topics in discussions of more localised effects: regional plate tectonics; relief by internal processes; lithology and erosion; topographic expressions of these processes as geological structure; regional drainage, drainage evolution and networks; palaeogeography; and Europe's regional geomorphology as an example.

4 'Local-scale geomorphology: process systems and landforms', more than a third of the book, describes processes in more detail: Weathering systems (mechanical, chemical and climate-driven); Slope processes (rockfalls and screes, other geological mass movements and landslides); Climatic effects on slope processes; Fluvial systems; Aeolian systems; Glacial systems; and Coastal systems (sea coasts, lakeshores, and erosional, depositional and biological effects on them).

5 'Timescale and landform evolution' begins with a landscape example: Quaternary Carlingill in Cumbria' .Then covers the expected: Relative dating and Absolute dating; followed by subsections on temporal and spacial scales, with two regional examples — upland north-west England, and the Sorbs basin in south-east Spain.

6 'Geomorphology and interactions with society' introduces the human influences on the landscape and its landforms. As an archaeologist, historian and geologist I naturally find this topic fascinating. As an undergraduate at UC Berkeley in the 1970s, studying archaeology, anthropology and history, one of the things that always impressed me was the example one of my medieval history professors included in his assigned reading list: the remarkable and ground-breaking book *The Historian's Craft* by the French historian Marc Bloch, written in 1949, translated into English in 1953. In it, Bloch ventures into fields 'outside' his area with the example of the decline of medieval "Belgium's" wool industry as the harbour of Bruges silted up and began to hamper the adjacent region's economic dominance in wool production and trade. Chapter 6 has only 10 pages, but the field is obviously vast and Harvey's introduction to it will hopefully encourage readers to explore more.

The text is enhanced by 72 figures and 3 multi-page, yellow-tinted 'Box' section on special topics, and a Table of the world's 'top ten' river systems. The figures include colour photographs illustrating landforms and geological examples, and line drawings and graphs explaining geological and geographical principles, processes and landforms.

The book is completed with a subdivided 'Further reading' list: 'Classics', 'High-school texts', 'University-level texts', 'Encyclopaedic works', 'Specialist fields (selected examples only)', and 'Useful websites'. And then a useful 'Glossary', which, with page numbers for each entry's place in the text, also serves as an index.

Prof. Harvey's book is readable and well worth its price.

— David M. Jones, OUGS Proceedings Editor

Podcast review

Geology Bites
Created and presented by Oliver Strimpel
https://www.geologybites.com

A review article by Caroline Peters

'Geology Bites' might suggest something light or inconsequential. But nothing could be further from the truth. Each *Geology Bites* podcast is a fascinating, in-depth conversation between the presenter, Oliver Strimpel, and a scientist whose work has shaped our understanding of the Earth.

In each half-hour (or so) podcast a leading scientist explains his or her research into an important aspect of Earth or Solar System science. Topics so far include the evolution of the Earth and other planets, plate tectonics, geophysics, geochronology, volcanism, palaeontology, geomorphology, geohazards and natural resources. A *Geology Bites* website has excellent supporting materials for each podcast, including maps, diagrams, images and videos.

Oliver Strimpel is a thoughtful interviewer, asking pertinent questions and occasionally providing clarification. His guests clearly enjoy talking with him about their work. As a former astrophysicist, visiting Earth Sciences fellow at the University of Oxford and ex-curator at the Science Museum, London, he has no difficulty in attracting distinguished speakers. For example:

• Paul Hoffman, famous for his Snowball Earth hypothesis, explains the compelling evidence for two Snowball Earth episodes around 720Ma and 635Ma and discusses current thinking on the circumstances that might have triggered these events (Fig. 1). *[Paul Hoffman on the Snowball Earth Hypothesis 1/11/2021]*

• Trilobite authority Richard Fortey describes the extraordinary diversity of trilobites and their role in establishing the geological timescale. He recounts how he eventually figured out the probable purpose of a curious trident-like projection from some Devonian trilobites' heads (Fig. 2). *[Richard Fortey on the Trilobite Chronometer 7/11/2021]*

Figure 1 Ice-rafted dropstone deforming underlying stratified deposits including carbonate turbidites, Ghaub Formation (Marinoan), NW Namibia. [Paul Hoffman on the Snowball Earth Hypothesis] (image courtesy of Paul Hoffman).

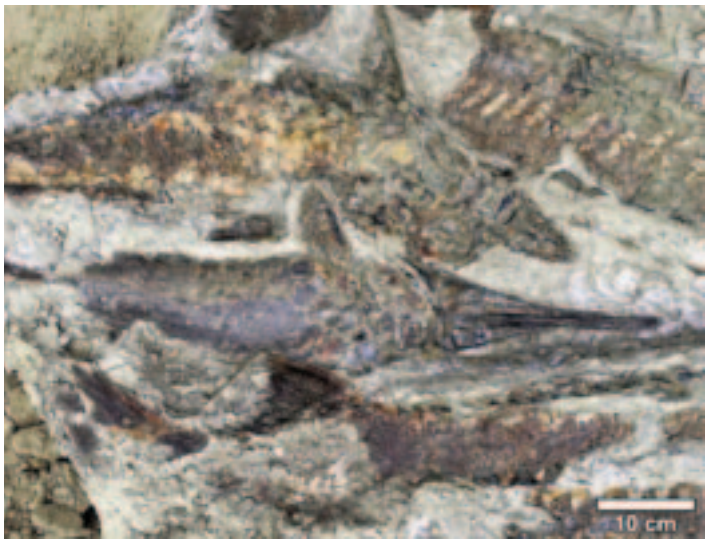
Figure 2 Trident-bearing trilobite from the middle Devonian, Atlas Mountains, Morocco. [Richard Fortey on the Trilobite Chronometer] (image courtesy of the Colorado School of Mines Geology Museum and Ron Wolf).

• Dan McKenzie, a founder of plate tectonics theory, reveals how Venus has provided an important insight into plate tectonics on Earth. *[Dan McKenzie on What Venus Can Tell Us About the Earth 29/7/2020]*

• Jan Smit, an originator of the asteroid impact hypothesis for the K-T (now K-Pg) extinction event, reveals some intricate palaeontological and other evidence used to deepen our understanding of this event (Fig. 3). *[Jan Smit on Resolving a Single Hour of the Cataclysm That Ended the Cretaceous 3/5/2021*]

Geology Bites podcasts frequently offer a fresh insight into, or challenge, widely accepted concepts. Mathilde Cannat, for example, describes the surprising variability of mid-ocean ridges in fascinating detail, explaining how different thermal regimes affect crustal thickness and deformation *[Mathilde Cannat on Mid-Ocean Ridges 19/8/2021]*. Gillian Foulger explains why,

Figure 3 Mass grave of fish carcasses washed up on a river bank by the passage of an earthquake-induced surge minutes after the end-Cretaceous meteor impact. [Jan Smit on Resolving a Single Hour of the Cataclysm that Ended the Cretaceous] (image courtesy of Jan Smit).



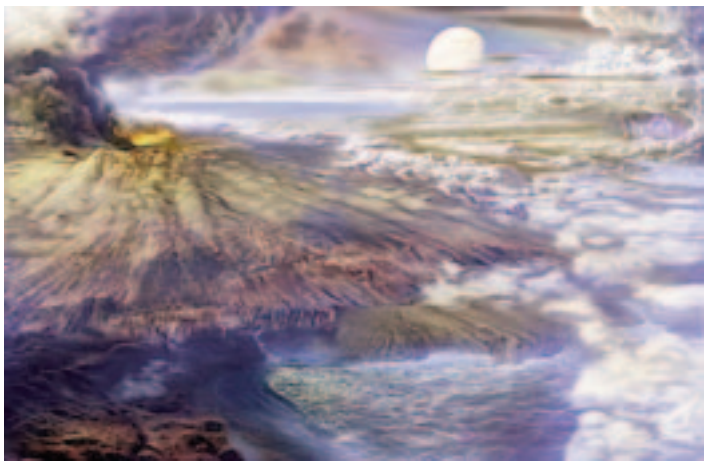


Figure 4 Artist's impression of a not so hellish Hadean with liquid water oceans, a basaltic shield volcano, and clement conditions. [John Valley on the Early Earth] (image courtesy of Don Dixon).

in her view, the evidence for a mantle plume in Iceland and other so-called 'hot spots' is by no means compelling and highlights some inconsistencies between the theoretical requirements to support the existence of mantle plumes and the current evidence *[Gillian Foulger on Explaining Intra-Plate Volcanism without Mantle Plumes 26/4/2021]*. John Valley reveals that after a relatively brief initial period, much of the Hadean was not at all hellish and could have fostered life (Fig. 4) *[John Valley on the Early Earth 20/9/2020]*. Lee Groat explains that, contrary to what he was taught, recent research shows that crystals in pegmatites are large not because they grew slowly but because they grew quickly (Fig. 5) *[Lee Groat on How Gemstones Form 7/3/2021]*.

A number of Geology Bites podcasts cover social and industrial aspects of geoscience. James Jackson discusses the 'fatal attraction' between cities and earthquakes and how the resulting risks can be mitigated *[James Jackson on the Fatal Attraction Between Cities and Earthquakes 28/7/2020]*. Kathryn Goodenough explains the geological settings in which lithium, essential for lithium-ion batteries, can be found, tempering the news that lithium is surprisingly

Figure 5 Blue spinels with white carbonate in a calc-silicate rock composed of the green amphibole pargasite, Baffin Island. [Lee Groat on How Gemstones Form] (image courtesy of Belley & Groat)

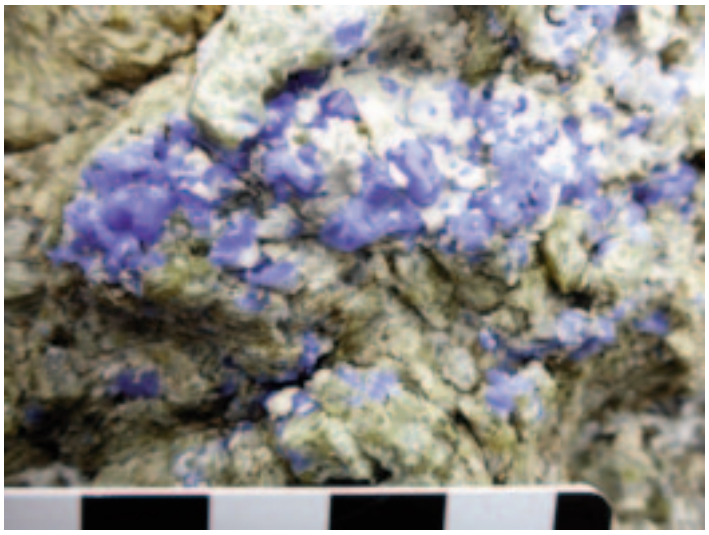


Figure 6 Ed Marshall sampling lava using a steel pole with a scoop welded to the end. Some samples are viscous like thick tar, others like 'molten marshmallow'. [Ed Marshall on Iceland's 2021 Eruption] (image courtesy of Ed Marshall).

widespread, with concerns about the economic and engineering hurdles to be overcome and the environmental impacts of extraction and processing *[Kathryn Goodenough on the Sources of Lithium for a Post-Carbon Society 9/8/2021]*. Mike Howe, speaking about the UK National Geological Repository, reveals the vast geological resources (many in digital form) available to industry, researchers and the public. Links, for example to the type fossil database, are included in the podcast materials *[Mike Howe on the UK National Geological Repository 14/3/2021]*.

Some podcasts discuss topical developments. Ed Marshall explains the evidence emerging from Iceland's Fagradalsfjall eruption, which commenced in March 2021 following an 800-year period of inactivity. If historical patterns are repeated, the eruption could be the start of a 400-year period of episodic volcanic activity in the Reykjanes region. Although a modest eruption, its importance is considerable, being the first eruption from the crust/mantle boundary that scientists have been able to study directly (Fig. 6) *[Ed Marshall on Iceland's 2021 Eruption 13/11/2021]*. Sue Smrekar, Principal Investigator for the upcoming VERITAS high-resolution mapping mission to Venus, explains the scope of the mission and what it could tell us about Venus' history *[Sue Smrekar on the VERITAS Mission to Venus 3/12/2021]*.

The podcasts mentioned here are only a few of more than 50 episodes available at the time of writing. Although there are occasional cross-references to other podcasts, each episode is free-standing. Start listening with any episode that piques your interest.

You can access *Geology Bites* through Spotify, Apple Podcasts and other podcast apps, and all browsers except Internet Explorer. I often listen directly from the website using my Android phone so I can view the supporting visual material simultaneously.

Oliver Strimpel set out to make *Geology Bites* accessible to curious listeners, including those without much scientific knowledge. He acknowledged that this might be optimistic given the 'subtle and intricate' nature of the material. I agree. But for any geoscience undergraduate or graduate, Geology Bites is a thoroughly enjoyable way to hear what is happening at the cutting edge of Earth and Solar System science from some of its foremost researchers and thinkers.

Use any podcast app to subscribe to future podcasts and explore over 50 previous episodes with their supporting materials from July 2020 to the present at https://www.geologybites.com

— Caroline Peters BSc (Hons) Geoscience (Open)

Other *Geology Bites* Podcasts include:

• Mike Searle on Ophiolite
• Peter Cawood on When Plate Tectonics Started
• Steve D'Hondt on Reviving a 100-Million-Year-Old Bacterial Colony
• Katie Stack on Mapping the Geology of Mars with the Perseverance Rover
• Marie Edmonds on Volcanic Gas
• Sarah Stewart on a New Scenario for How the Moon Formed
• David Evans on Supercontinents
• David Rothery on Volcanism in the Solar System
• John Marshall on the Riddle of the Mass Extinction 360 Million Years Ago
•Laurent Jolivet on the Origin of the Mediterranean
• Bruce Buffett on Probing the Earth's Core
Sara Russell on What the Asteroids Can Tell Us About the Earth
• Clare Warren on Divining the History of a Rock
• Steve Sparks on What Makes a Volcano Erupt

David Maddocks
(14 August 1947–3 November 2021)

David Maddocks held prominent roles within the Society for many years. In 1995 he was the Walton Hall Branch Organiser and after two years, he then joined the Executive Committee as Events Officer from 1997 to 2001. David was Chair of our Society from 2002 to 2005 and all members who knew him are grateful for the work that he undertook and the time he gave to the Open University Geological Society.

He is fondly remembered by many, not only for his major contributions to our Society, but also for his wonderful sense of humour. Many also recall the Society trips that he and his wife Elizabeth organised for the Society, particularly those to Namibia. Those who were fortunate to have attended these are grateful to both David and Elizabeth for the time they gave.

"Dave took over as OUGS Chair in 2002, and I was then the Society's Secretary. I had just gone back to work full time at the OU in Bristol and got terrible stick from Dave for leaving him to cope with his first AGM (in Bristol as it happened) without the support of a Secretary, as the university wanted me in Taunton that afternoon. I made sure I never did that again, and enjoyed four years of working with him, not least because of his great sense of humour!" [from Linda Fowler]

"I really enjoyed working with David. He became OUGS Chair in the same year that a new OUGS Newsletter Editor was needed and elected — me. David always gave me his full support and encouragement; and I remember many interesting talks on geology with him, and with Elizabeth and Jane Clarke, when we all rode together to Birmingham for committee meetings. I commend David especially for one of the OUGS projects we completed during his tenure as Chair: the OUGS book, Durham 25: A Celebration of 25 Years of OU Geology Summer Schools at Durham by John S. Watson, which we launched at the OUGS Symposium in Durham in June 2003. I, too, appreciated David's subtle, gentle sense of humour." [from David M. Jones]

"While I was Chair, David Maddocks was the Events Officer. He had a lot of experience in event organisation, which he put to good use. I had a memorable weekend at David and Elizabeth Maddock's home, finalising his draft protocol for the Symposium, which I believe is still in use today. His good humour and daft jokes were always welcome at committee meetings." [from John Lamont]

"I first got to know David Maddocks when I joined the Executive as Society Treasurer in 2000. He was a fun person, always ready with a witty comment or a joke. He could see the funny side of most things. Whilst I never went on one of his Namibia trips they sounded great fun and really interesting. He gave a talk on the first one when he got back and it left me with a feeling of a place I would like to visit (but haven't yet, other places were slightly higher up the bucket list order!). He'd done such a lot of research etc. to make it a great trip. He was also very helpful when I took over as Librarian/Archivist in 2006 from his wife Elizabeth. He helped me get the 21 boxes of books and papers safely stacked in my (then) 18-month-old Jazz: no mean feat! Although I didn't meet up with him much after that, I will always have fond memories of him and Elizabeth. He will be missed." [from Jane Michael]

I first met David at the Open University Geological Society Symposium at St Andrews University in 1993, which coincidently was also the event that I first met Elizabeth and my partner Patricia. So quite a momentous event for all four of us, and carried us through the past notable 28 years.

David was a person who had a large range of interests, a very quick intelligence and a huge sense of humour, but more of that later.

The list of his interests is long and gets longer as I think about it: geology, birds, African wildlife, trains, fishing, water conservation, Bridge, ice cream, climate care, environment, weather and computing to name a few.

He never missed the opportunity to have an ice cream wherever he was. Possibly to the exclusion of all his other interests.

If you had a computer or TV set up problem, he was the person to go to. He was always helpful and knowledgeable.

I think that anyone who knew David would identify him with his sense of humour. He used to make us laugh and groan in equal measure with his constant jokes, innuendoes and puns. Elizabeth must have heard his jokes a thousand times and I don't know how she kept a straight face. He was very quick witted and you had to be alert not to be taken in by his responses. We tried hard not to laugh just to annoy him but failed most of the time.

I would say his favourite joke of so many was about: The Butcher — who accidently sat on his bacon slicer — he got behind with his orders!

I wonder how many times we have heard that one and so many others?

"David was such an interesting person to know and was great company; and had an answer to nearly everything. We will miss him greatly." [from Mike Moores]

I echo all the tributes that have been sent by so many who knew David. He will indeed be missed.

— Pauline Kirtley, OUGS Secretary

Jane Clarke
(25 February 1944–12 January 2022)

Honorary Member of The Open University Geological Society and founder member of the Dorset Geologists Association Group.

It is with sadness I am writing this obituary for Jane Clarke, who I have known since I joined the geology groups in 1995. Jane had Parkinson's Disease for many years and passed away in hospital on 12 January 2022.

Jane studied Earth Sciences with the Open University in the early days and achieved a BA, then a BSc (Hons) and an MPhil. She was particularly interested in palaeontology and developed this by joining OUGS in 1986. She and her husband Trevor were extremely supportive to palaeontologist Steve Etches in helping him to write up papers and to make the successful bid for his fossil collection to become a public museum: The Etches Collection in Kimmeridge.

In 1993, because of plans to replenish the beach with Tertiary gravels as coastal defences in Ringstead Bay, Jane joined with a few others to form the Dorset Geologists Association Group (DGAG) to protest this. The Ringstead Bay SSSI, designated because of the unique Ringstead waxy clay and coral beds, was subsequently overwhelmed by the river gravels. However, DGAG went from strength to strength, thanks to the founder members determination.

Jane was very actively involved in the Open University Geological Society. She was Branch Organiser of the Wessex Branch for a number of years until the mid-1990s and helped to organise several Symposia. She used to produce the Wessex Newsletter and went on to edit the National *OUGS Journal* from 1991 to 2007. Jane was active in OUGS national committee meetings and very supportive to members. As a result of the excellent editing of the *Journal*, Jane was awarded honorary membership on her retirement. She was extremely supportive to David Jones who subsequently became Journal Editor.

Here are some comments by David Jones:

"I met Jane and Trevor when I became Newsletter Editor in 2002 and started attending OUGSEC meetings in Birmingham. David Maddocks was Chair, and he, Elizabeth, Jane and I would often travel together to the meetings. Of course, we also always saw each other at AGMs and Symposia.

In 2007, towards the end of my last term as NL Editor Jane asked me if I would be interested in the editorship of the Journal*. She told me that she was ready to step down, and that if I was interested, she wanted to put my name forward to the EC. The Journal Editorship is a co-opted position rather than an elected one by the OUGS membership; and is assessed every year by the Committee.*

When I succeeded Jane as Journal Editor she was most helpful in my early years. She helped me with the cover design, which had been done by her daughter, and with many images and figures in the Journal *articles. We also worked closely together in upgrading the QuarkXPress design software used for the* Journal *and* OUGS Newsletter *editing, page layout and print preparation.*

At AGM and Symposium both Jane and Trevor were generous with their help to me in those first years as Journal Editor. They would help me with all the arrangements to set-up for recording the lectures, and in finding transcribers to provide the written texts of the lectures for the speakers for their Journal articles. Jane would often transcribe one of the lectures herself; and Trevor was most helpful with electrical connections and set-up of the recording equipment — for back in those early days we used cassette recordings and there were no podium set-ups and 'tech support"people as we now have in modern conference centres!

I will always have fond memories of Jane and Trevor and remember the help they gave me."

Jane and Trevor came with me and other OUGS members on a self-led trip to Iceland in 2001. We had several experts among us, including Jane.

Below are comments about Jane and this trip from Lawrie Bubb, Wessex member:

"My first memory of Jane was when she gave a lecture at our AGM on the bone structure of the Aves, comparing ancient and modern. I have always thought about birds in a different light since then, especially when I see birds of prey soaring on thermals. Or a seagull gliding into a landing.

Another memory that occasionally passes through my mind is when we were in Iceland 2001. A group of us were walking along a beach late in the evening in glorious sunshine. Jane had found a half rotted dead sea bird and was carrying it to take it home for research. She explained if you leave it in the garden for a while nature will strip the bones clean. Just after that Sheila looked at her watch and said, 'Do you realise, it's two o'clock in the morning'.

Trevor was the independent financial examiner whilst I was treasurer of Wessex OUGS. Always an interesting visit when I took the books over to him. They were involved in the early days of Steve Etches' Museum at that time. Both Trevor and Jane always had something interesting to chat about.

I have in front of me right now the book that Jane co-authored with Steve Etches, Life in the Jurassic Seas*. It's a signed copy that Jane gave to me on one of my visits; it will mean that much more to me now."*

Over recent years Jane was disabled by Parkinson's Disease so unable to actively participate in geology events in person. Nevertheless, she remained interested in geology and used to send positive feedback regularly to the current Wessex Newsletter editor. I have received many appreciative comments about Jane from her geology circle of friends. Our thoughts are with her husband Trevor and family. Jane will very much be missed.

— Sheila Alderman, OUGS Wessex

The Society notes with sadness the passing of the following members in 2021 and early 2022:

Alan Dyer (Walton Hall)
Alex Hickman (London)
Brian Smith (North West)
Colin Davies (Walton Hall)
Earl Haworth (Nene-Tees)
Gerard Shaw (Nene-Tees)
Gerry Tasker (Northumbria)
Hilary Davies (North West)
Keith Varley (London)
Mavis Gill (Northumbria)
Michael Sandison (East Anglia)
Ofori Kwame (London)
Paul Over (London)
Roger LeVoir (London)
Tim Walker (Walton Hall)
Wilf Walker (London)

Editor's notes to contributors

Following are guidelines for the submission of articles to the *Proceedings of the OUGS*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Proceedings*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention — I will probably spot them anyway — so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Proceedings* articles

As OUGS Proceedings Editor I do not want the publication of your article to be more work than is necessary for you (or for me!). Your article need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material you are writing about.

Regarding articles from the presenters of lectures at the OUGS AGM and Symposium, all OUGS members are grateful to you for presenting a lecture to us on your research, and for agreeing to submit a version of your talk for publication in the *Proceedings*. The purpose of this is to make your information available to OUGS members and others who could not attend the Symposium. As OU students and OUGS members we enjoy hearing and learning the information these events bring to us.

All that is necessary are:

• A Word (or compatible) file of the text: There is no need for you to attempt to format the text in any way using tools in Word or other word-processing software. I will do the page layout format in the *Proceedings* house style, using dedicated publication-industry-standard page-layout software (QuarkXPress). However, feel free, if you wish, to use **bold** and/or *italics* to indicate headings and subheadings so that I can identify and set these into house style.

I do not require a hard copy, but if you need to point out special characters or attributes in your article, it may be a good idea to send one with these items marked up or otherwise highlighted. I can accept electronic files attached to e-mails, text and image files on a CD or on a flash drive, or via shared media.

• Each illustration, chart, graph, map or other illustration as a separate digital file in high resolution: 300dpi minimum for colour or half-tone images; as high a dpi as possible, please, for line illustrations. Tables composed in Word or Excel are fine, as they are just text. A rough guide to the number of figures in an article is 10 to 30. Obviously as an AGM or Symposium presentation speaker you might have shown numerous slides, so please use your best judgement on the number to publish with your article — again, usually 10 to 30 is only a rough guide.

• Please be sure that we have permission to publish any illustrations that are not yours: Also, please give me the appropriate information to cite in acknowledgement in the figure caption; and please tell me in writing or in an e-mail message that you have obtained the permission necessary for each illustration in your article that is not yours.
As the author, this responsibility is yours.

• Please do *not* embed your illustrations in Word picture boxes within the text: All that is necessary is to indicate, by a reference within ( ) or within [ ] in your text, where the illustrations should go.

• You can submit the material as attachments to e-mails to me or send it to me on a CD or flash drive: I am on BT Broadband, so I can receive large files. It is usually best to attach only a few illustration files each to several e-mails. This applies especially to large files of photographs, charts and graphs. Alternatively, a digital sharing package can be used, such as Dropbox or similar.

• Where appropriate, cite your sources, or make it clear that a statement is a supposition, or solely your own view or opinion. We use Harvard-style citations in the text: (author date, pages), e.g. (Jones 2004, 51–3); and your sources or references should be listed in alphabetical order by author and date at the end of your article. You need to list the author, date of publication (or of access to a website), full title, periodical volume or number, or place of publication and publisher, and page numbers.

If you miss out anything, I will ask you for it.

If your list includes items not cited in your text, it will be called 'Sources'; if all items in your list have been cited in your text, it will be called 'References'.

That really is it! The editing and page layout are my job, so let me do it for you. I will communicate with you, as necessary, as I do this, with queries or difficulties with any formats, special symbols, characters, etc, as is the task of any editor.

For you really keen authors, regarding grammar and spelling I use:

Butcher, J. 1992 *Copy-Editing: The Cambridge Handbook for Editors, Authors and Publishers* (3rd edn). Cambridge: Cambridge UP

The Oxford English Dictionary

The Penguin Spelling Dictionary 1990. London: Penguin Books Ltd

Ritter, R. M. (ed and comp.) 2000 *The Oxford Dictionary for Writers and Editors* (2nd edn). Oxford: Oxford UP

Ritter, R. M. (ed and comp.) 2002 *The Oxford Manual of Style*. Oxford: Oxford UP

Please feel free to contact me at any time about your article:

Dr David M. Jones, *OUGS Proceedings* Editor, 41 Blackburn Way, Godalming, Surrey GU7 1JY; 01483 424308;
proceedings@ougs.org

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Geologically inspired landscape, structure or feature in the British Isles, Winner — Michael McEllin

Malham limestone pavement, Yorkshire: Malham provides some of the best examples of limestone pavements in the UK, and the texture is best appreciated when the light is low. This view is just above the famous Malham Cove.

OUGS Moyra Eldridge Photographic Competition 2021

Winning and Highly Commended photographs

Geologically inspired landscape, structure or feature, British Isles, Runner-up — Ric Bithell

Cliffs of Moher, County Clare, Ireland: The Cliffs of Moher are a famous tourist attraction on the edge of the Burren in County Clare, Ireland. In contrast to the typical limestone of the Burren region, the cliffs expose Upper Carboniferous shales, siltstones and sandstones deposited by a large deltaic system into an ancient marine basin.

Geologically inspired landscape, structure or feature anywhere else in the world, Winner — Maggie Deytrikh

Mt St Helens, Cascade Range Washington State, USA: Mount St Helens, Washington State USA, taken July 2017, showing the remains of the volcanic edifice after its catastrophic eruption in May 1980.

Geologically inspired landscape, structure or feature elsewhere in the world, Highly Commended — Ric Bithell

Submarine volcanic deposits at Nishi-izu, Japan: The Izu Peninsula, west of Tokyo, sits on the Philippine Plate — the only part of Japan on oceanic plate. The Dogashima coast on the west side of the peninsula shows the results of submarine volcanism between ten and two million years ago, before the region collided with mainland Honshu. The deposits are part of the Shirahama group, consisting of white volcanic ash, pumice and subaqueous volcaniclastic flows.

Industrial geology, Winner — Ric Bithell

Marble quarrying at Fivizzano, Province of Massa and Carrara, Italy: he picture shows Carrara marble being quarried at the Cava Vittoria (named after Britain's Queen Victoria) at Fivizzano in 2017. Around the time of our visit, there were newspaper reports of illegal dumping and health and safety offences, and I believe the quarry is no longer operating.

Industrial geology, Highly Commended — Michelle Thomas
Clee Hill sill, W. Midlands, UK: Taken at viewing point at Clee Hill Quarry on 01-09-2018 on West Midlands branch trip. Shows the imposing 60m high sill of olivine-dolerite overlain by Carboniferous coal measures, with quarry machinery at the far end.

Industrial geology, Highly Commended — Michael McEllin
Lead mining in Swaledale, UK: Lead Mining in Swaledale: Gunnerside Gill is full of old industrial lead-in workings, but some of the earliest evidence is in the 'hushes' — gullies where the miners built dams at the top to trap water, then broke the dam to scour the surface soil away from the rock, so they could access mineral seams. Later, they tunnelled into the valley side.

Mineral, rock or fossil specimen, or thin section/SEM view, Winner — Linda Fowler
***Tyrannosaurus rex,* Altmuehltal Dinosaur Park, Bavaria.**

Mineral, rock or fossil specimen, or thin section/SEM view, Highly Commended — Linda Fowler
Leptolepides, a fresh water and marine bony fish, Solnhofen Formation, Langenaltheim, Bavaria

Popular Vote Winner —Ric Bithell

Smoo Cave in Durness, north-west Highlands of Scotland: Smoo Cave is a combined sea cave and freshwater cave set into cliffs at Durness, on the north coast of Scotland. The rear part is a karst cave formed inside limestones of the Durness Group. The Durness Group comprises limestones and dolomites formed during the Ordovician and Cambrian periods. The entrance to the cave has been greatly enlarged by sea action. The picture shows the second chamber, where Smoo Burn drops into the cave through a sinkhole.